Structure of Moist Convection in Planetary Atmospheres

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Outline

- Introduction
  - Examples of clouds in planetary atmospheres
- Short summary on clouds
  - Elements on convective instability
  - Elements on cloud microphysics
- Condensation and buoyancy
- Classification of convective clouds in planetary atmospheres
- Roles of cloud convection

PRECAUTION

I will discuss some thermodynamics, but , re-examine the content carefully if you become interested in it.

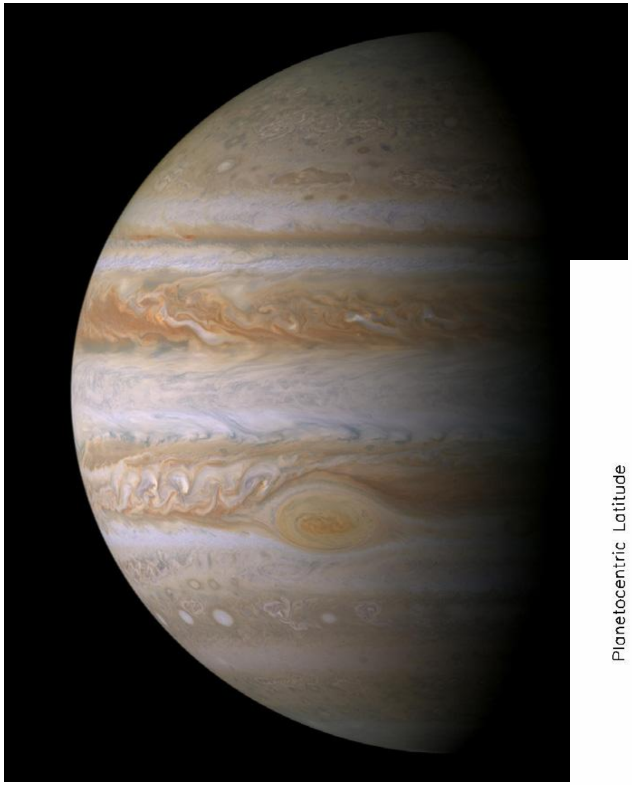
In 1988 Yutaka Abe said to me :

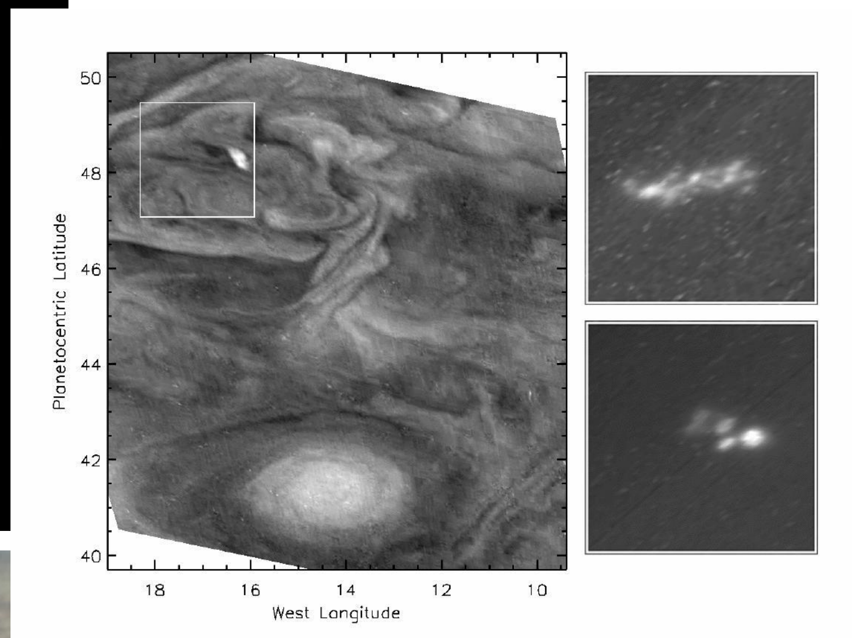
“*If you want to use something as a tool for research, you have to understand it to the extent in which you can use it even in your dream (while sleeping)*”.

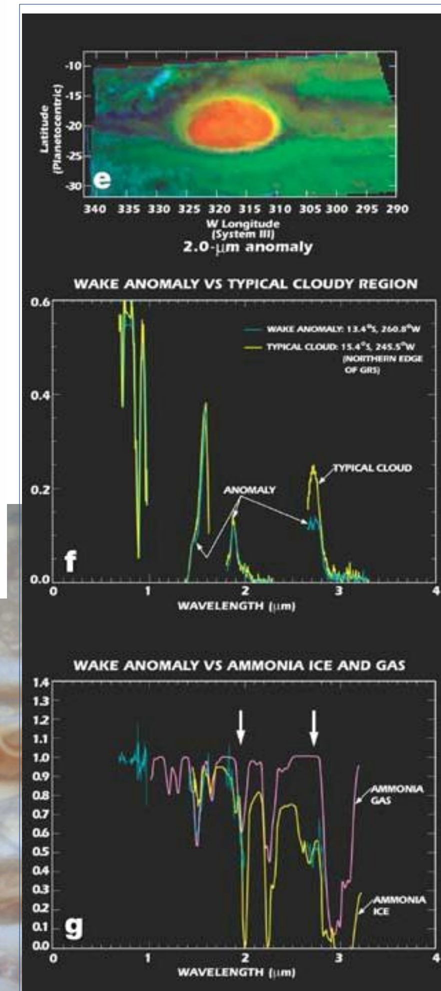
My knowledge on thermodynamics is far from that state.

Examples of clouds in planetary atmospheres

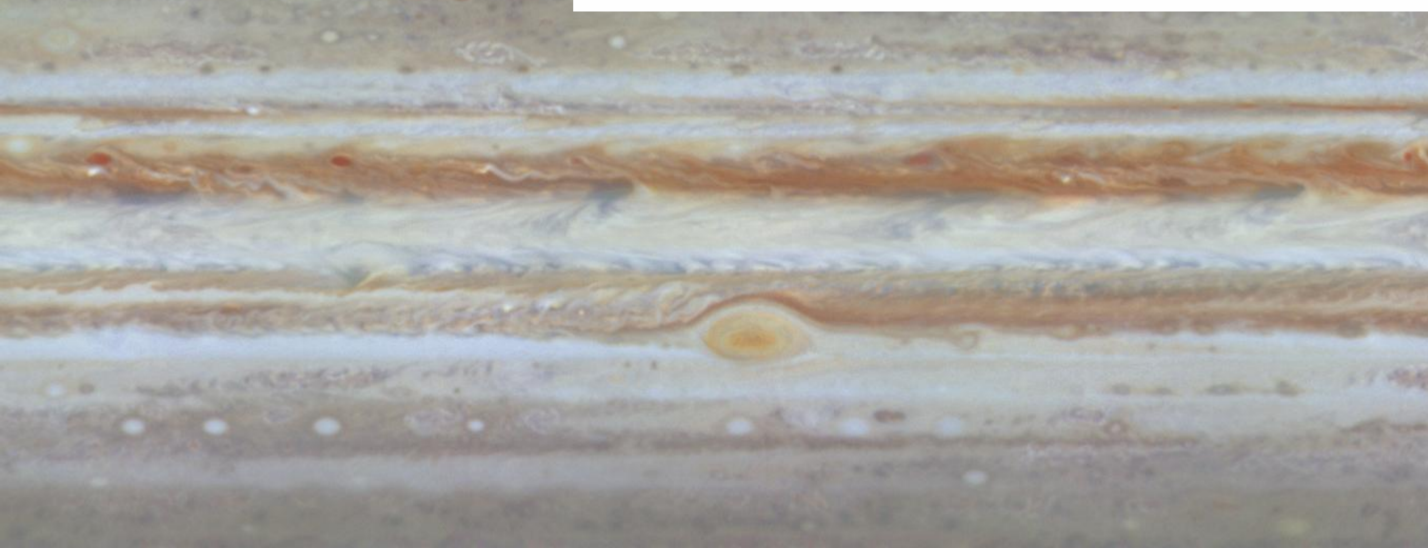
Jovian Thunderstorm



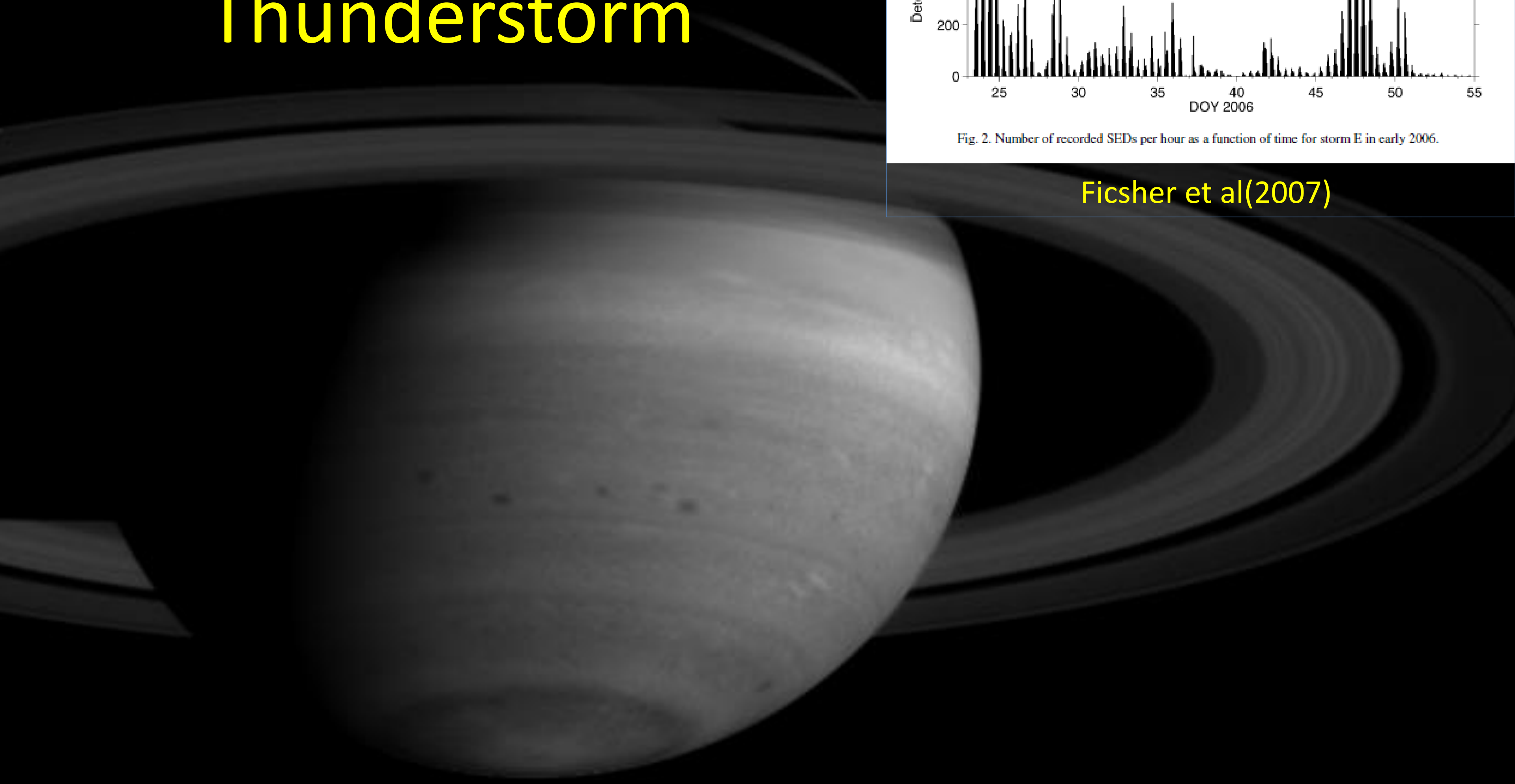




Baines et al(2002)



Saturnian Thunderstorm



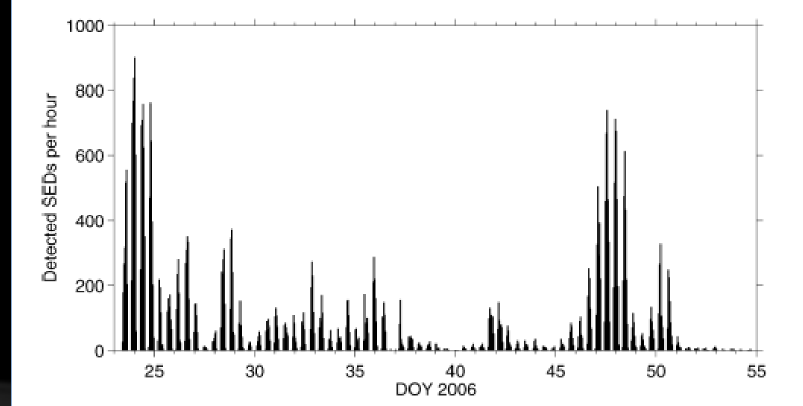
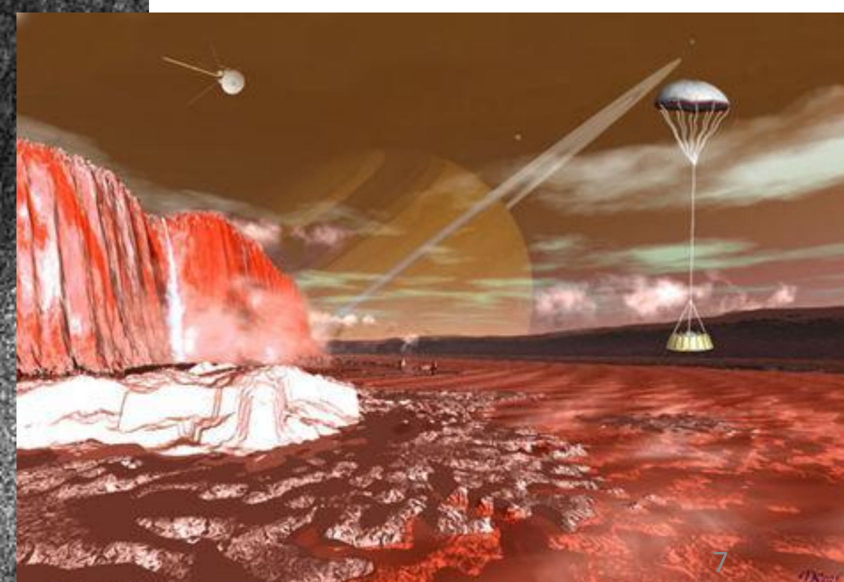


Fig. 2. Number of recorded SEDs per hour as a function of time for storm E in early 2006.

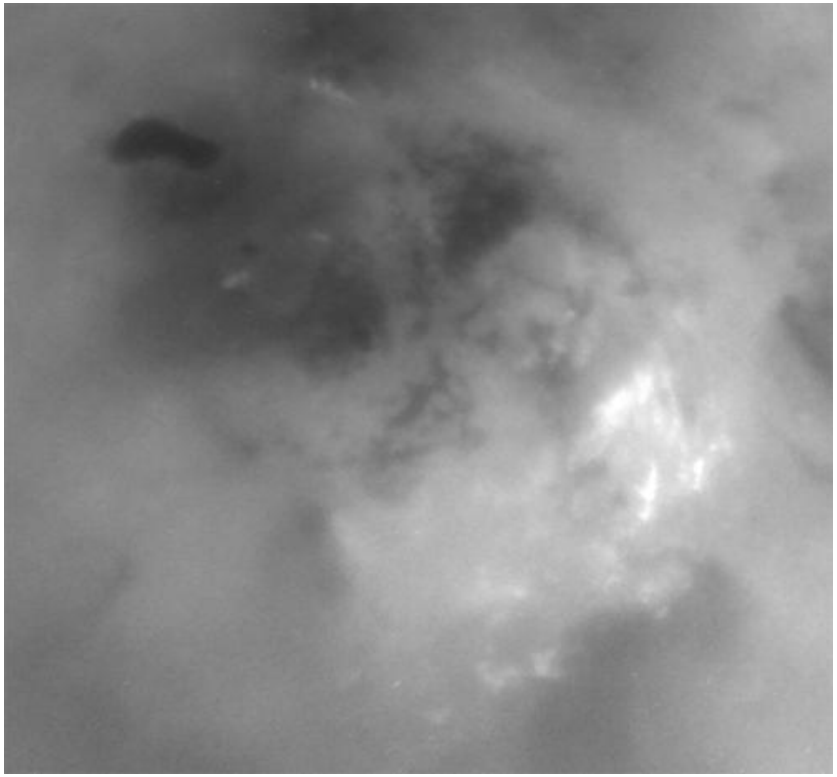
Ficsher et al(2007)

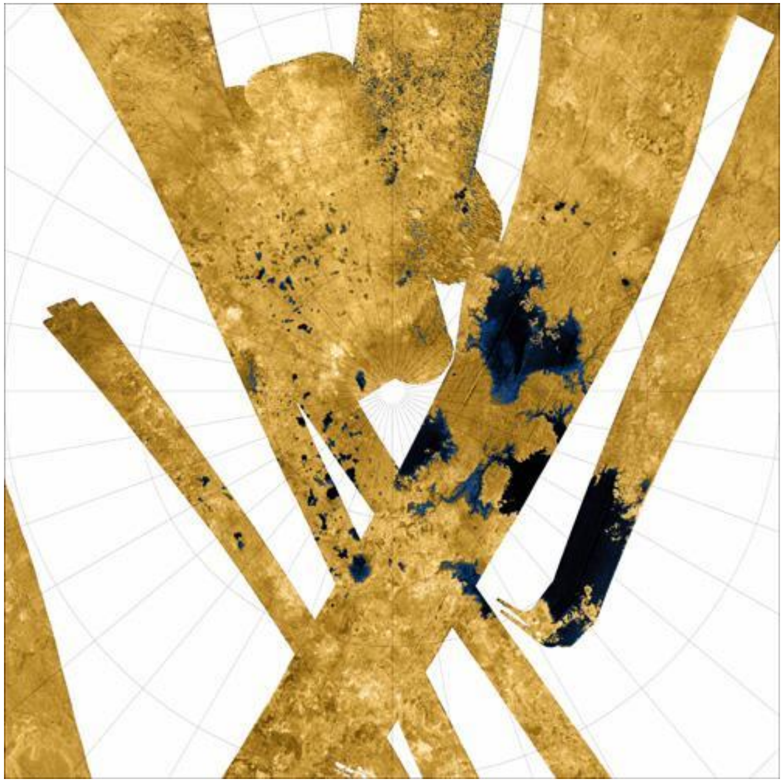
Titan’s lower atmosphere revealed by Cassini/Huygens



Surface was not Ocean
but Desert-like.

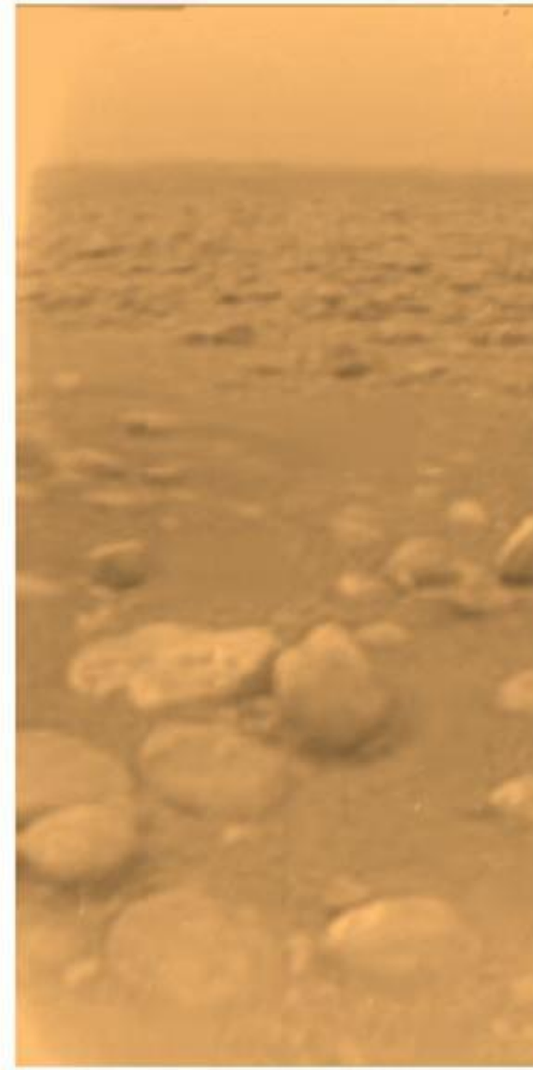
Convective cloud and Lakes





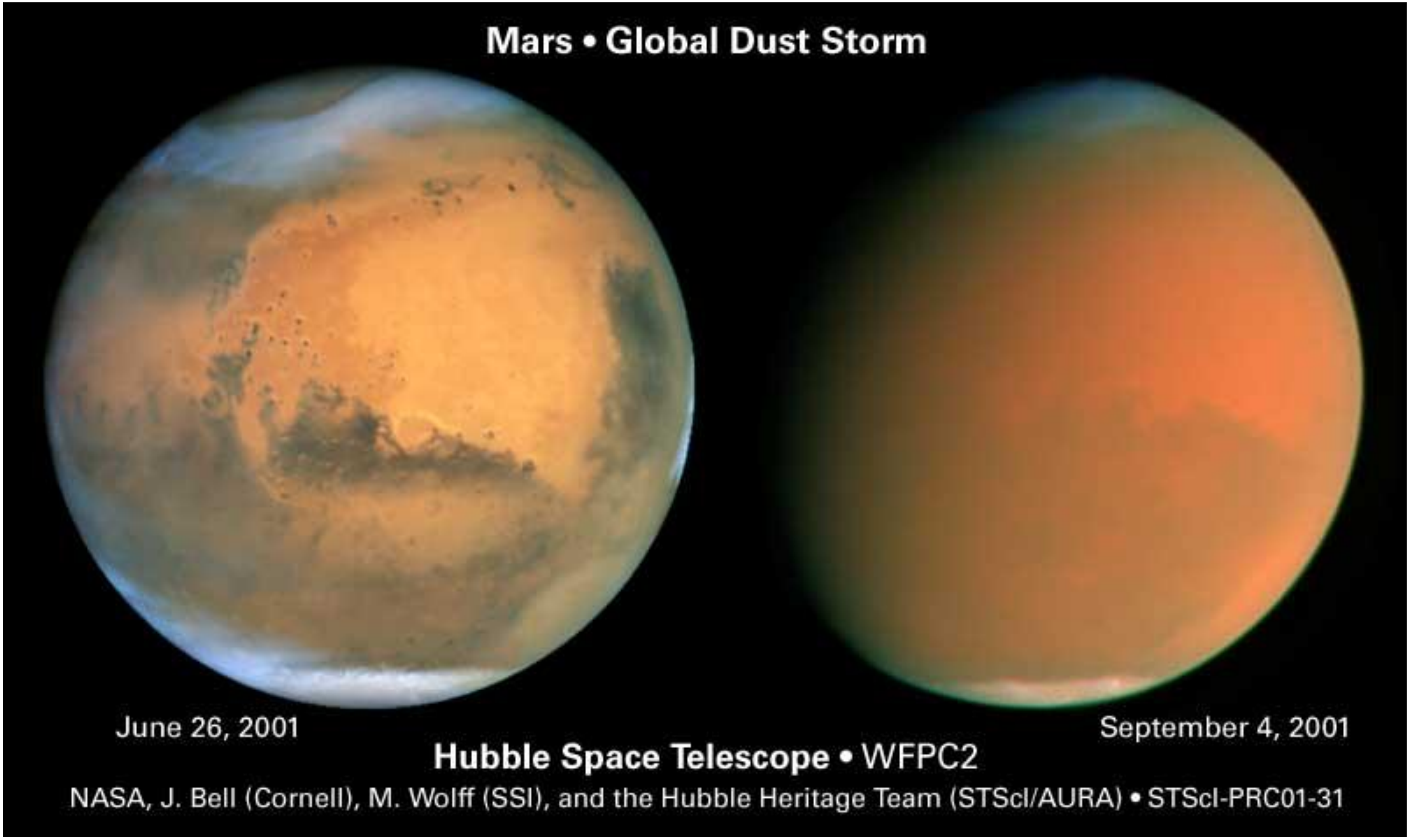
Signature of liquid (Huygens)

River-like feature



Methane "steam" from heated soil at the landing site

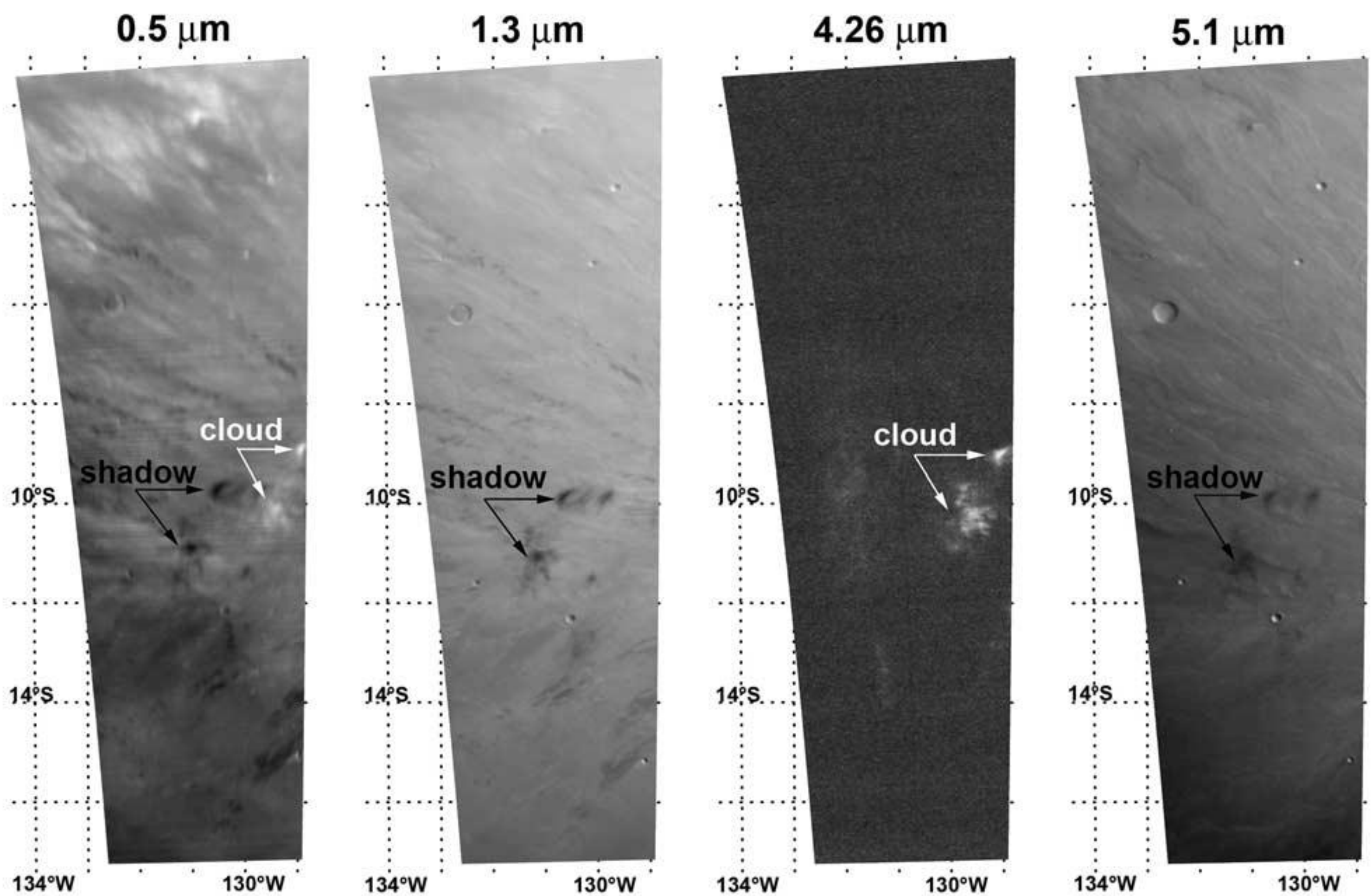
Mars: clouds of H_2O, CO_2, Dusts



Cirrus-like water ice cloud in Martian atmosphere

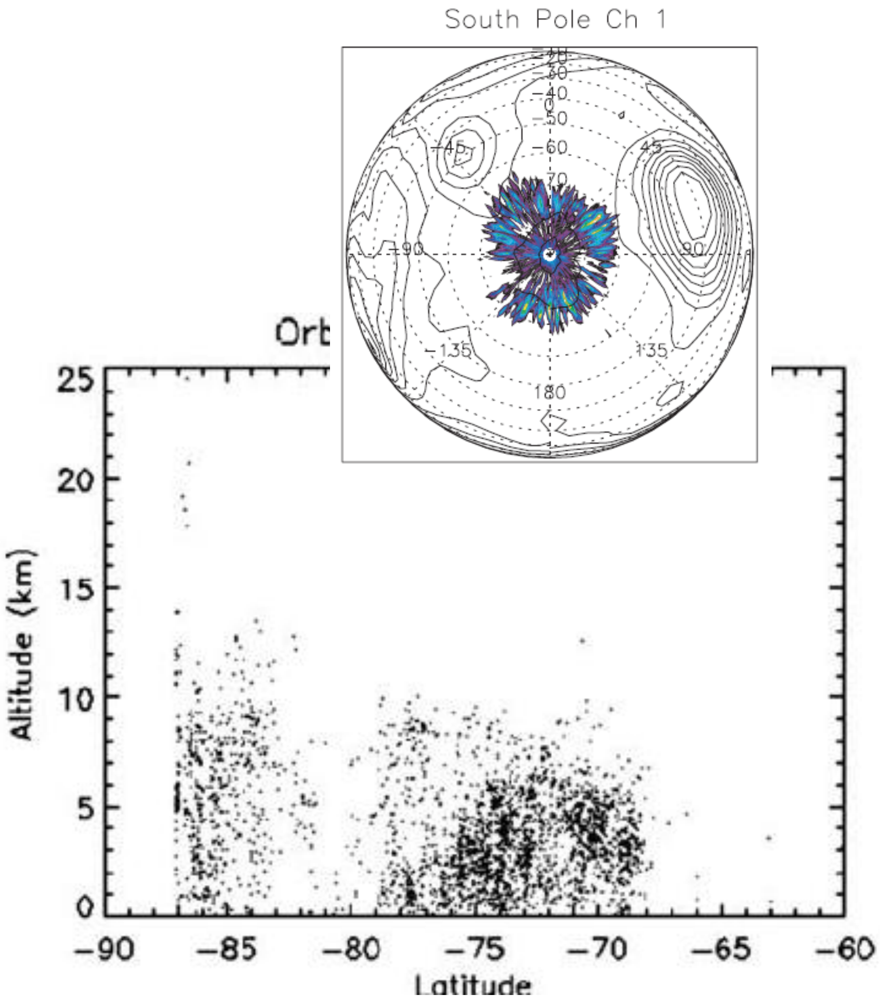
http://marsprogram.jpl.nasa.gov/MPF/science/clouds.html

High altitude (80km) CO_2 clouds observed by OMEGA (Mars Express)

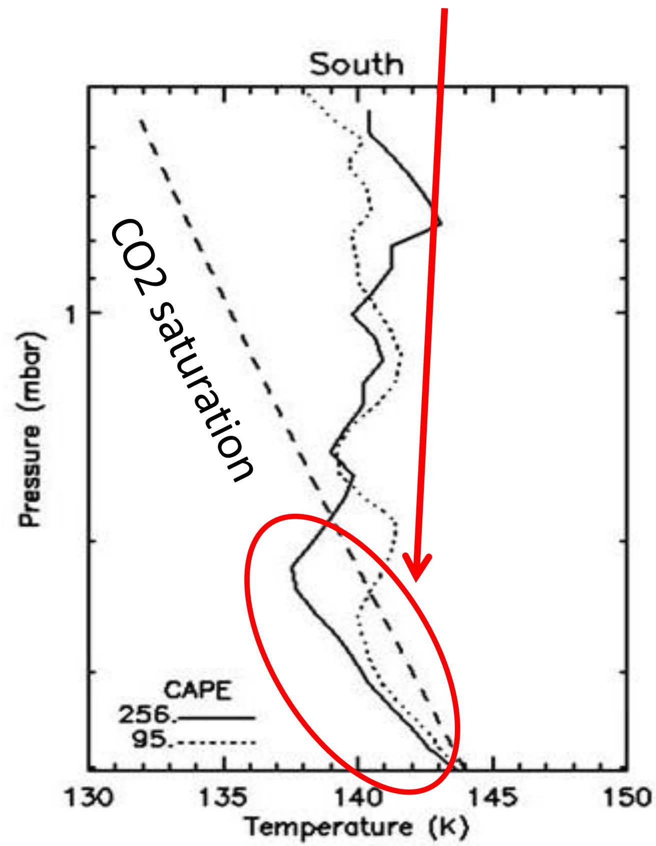


Montmessin et al (2007)

CO2 “Convective clouds” in Martian south polar region



super cooled state



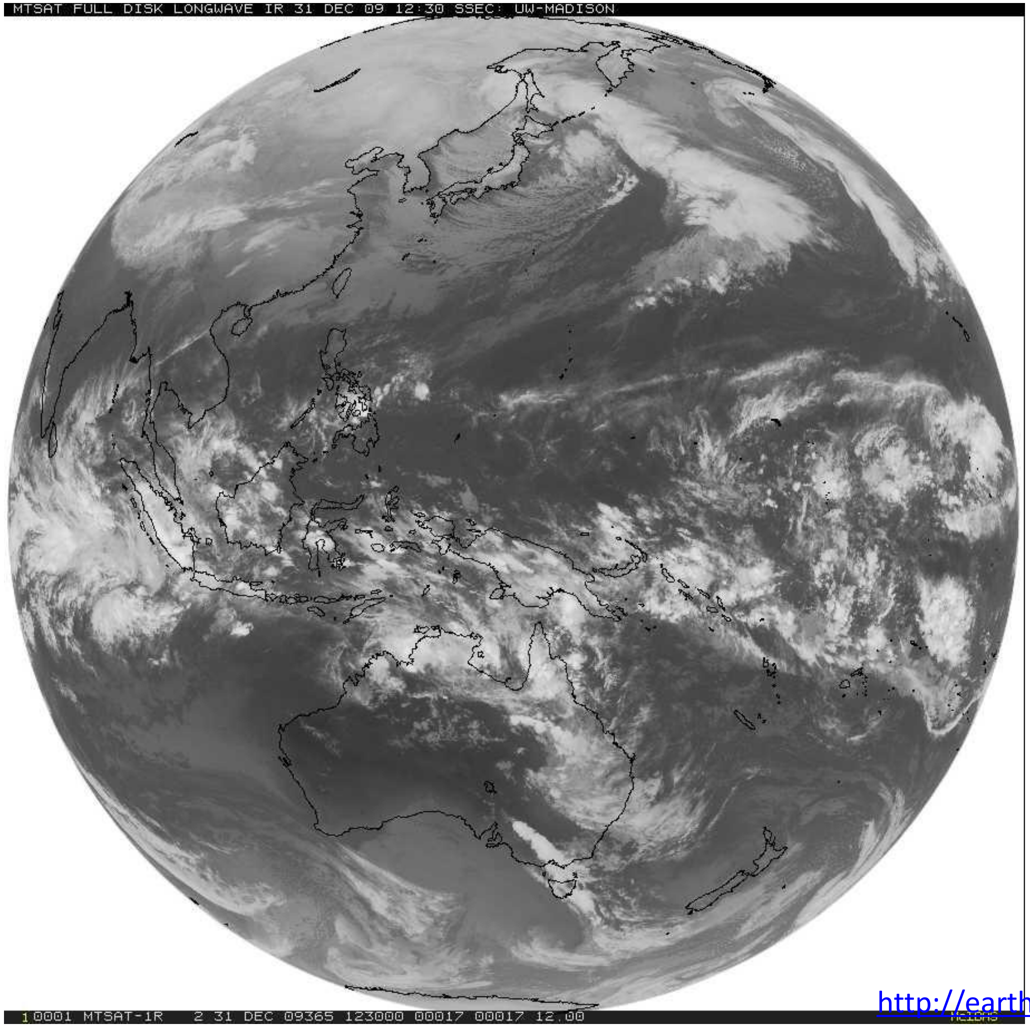
Colaprete et al (2003)

Earth’s water clouds

The only place where we have detailed knowledge on clouds.

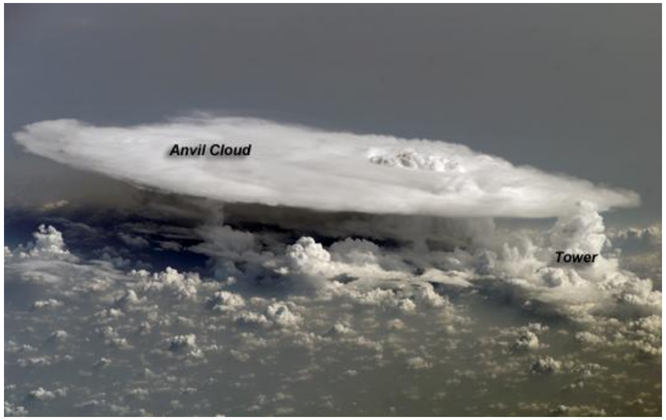
Thunderclouds

from space: “clusters” of 100-1000km scale are seen.



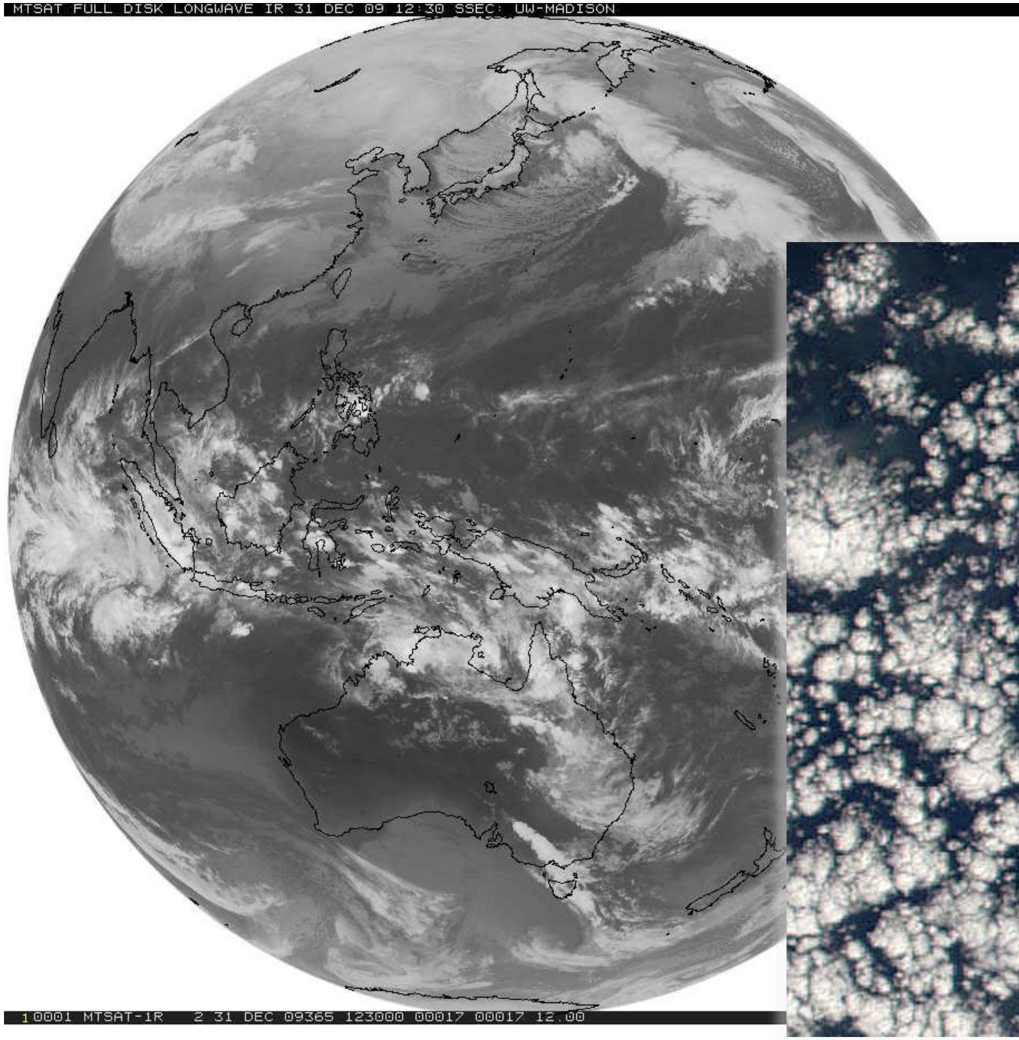
Indivisual updraft: O(10km)

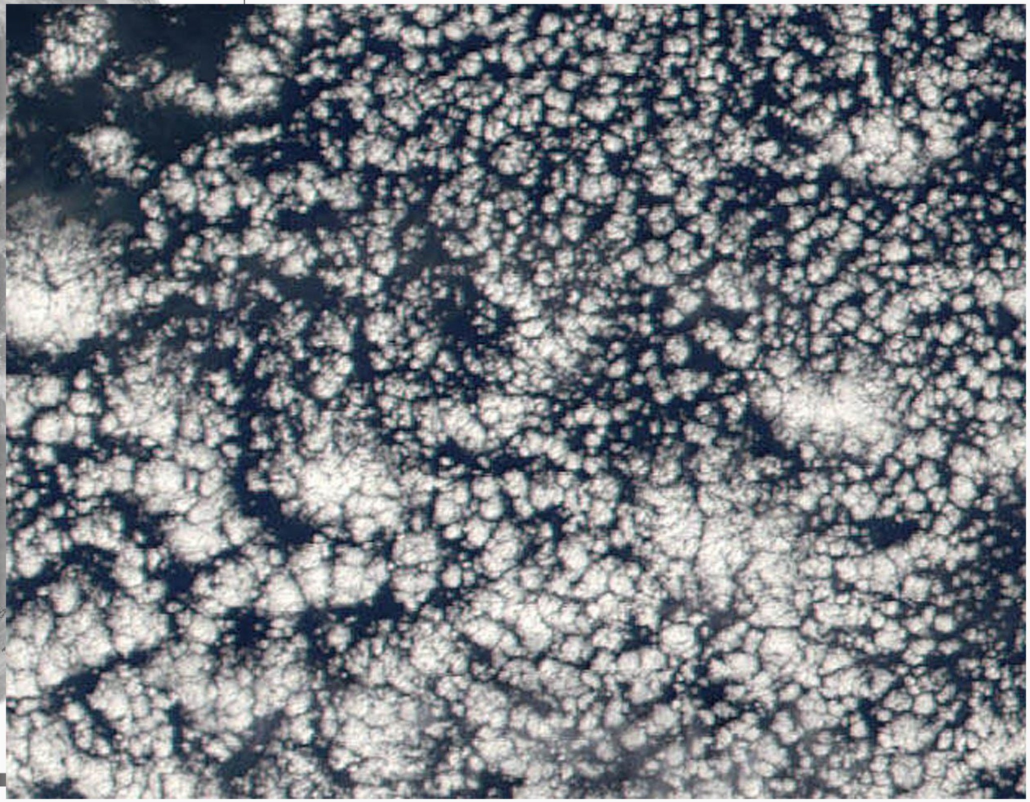
http://en.wikipedia.org/wiki/Cumulonimbus_cloud



http://earth.jsc.nasa.gov/sseop/EFS/images.pl?photo=ISS016-E-27426

smaller scale convective clouds





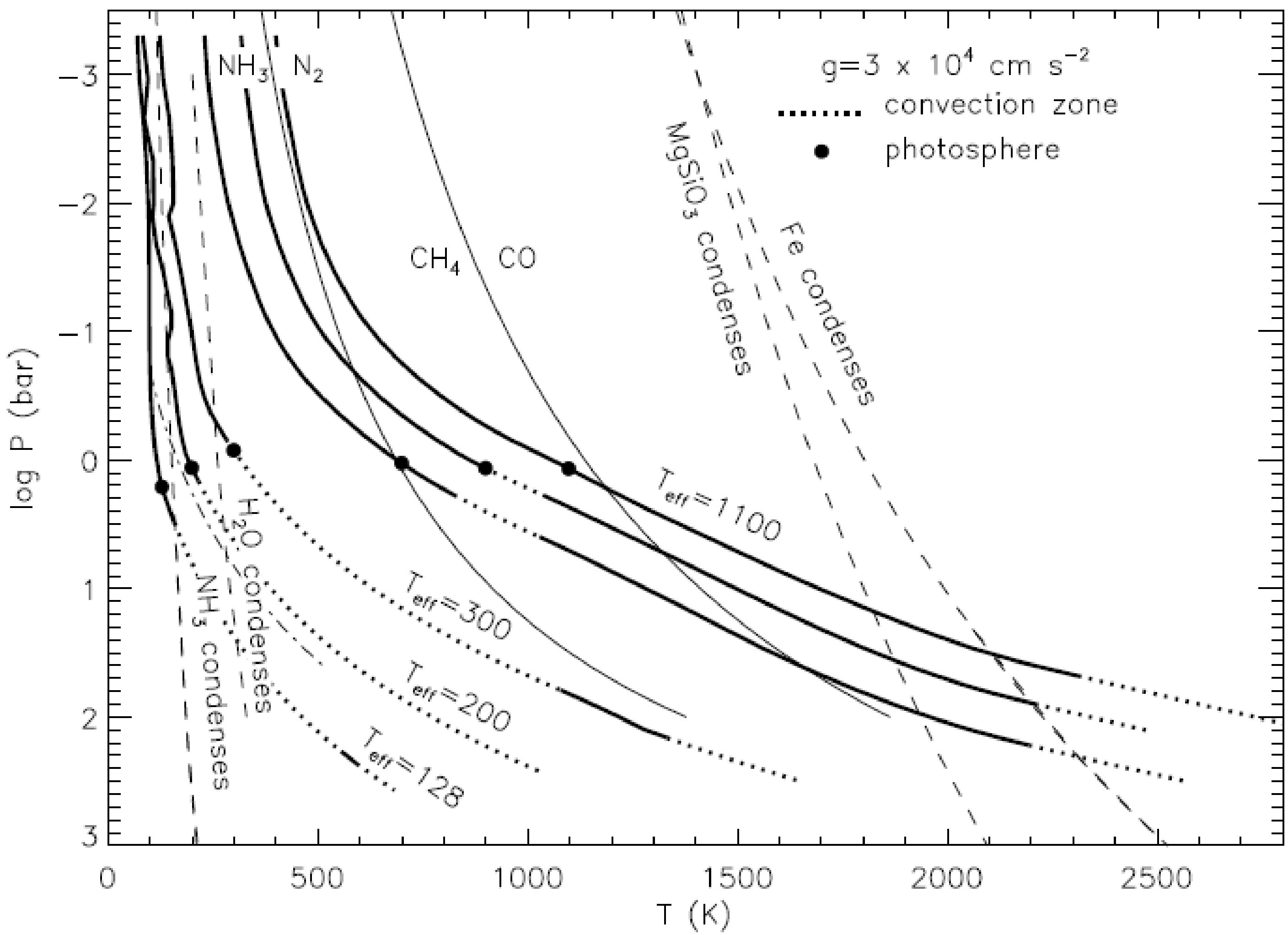
http://www.solarviews.com/cap/earth/cells.htm

Even Cirrus clouds have some convective character

Apparently “stratiform” clouds in the atmospheres of other planets may well be more or less convective clouds.

http://en.wikipedia.org/wiki/Cirrus_cloud
http://en.wikipedia.org/wiki/Cirrostratus_cloud
http://en.wikipedia.org/wiki/Cirrocumulus_cloud

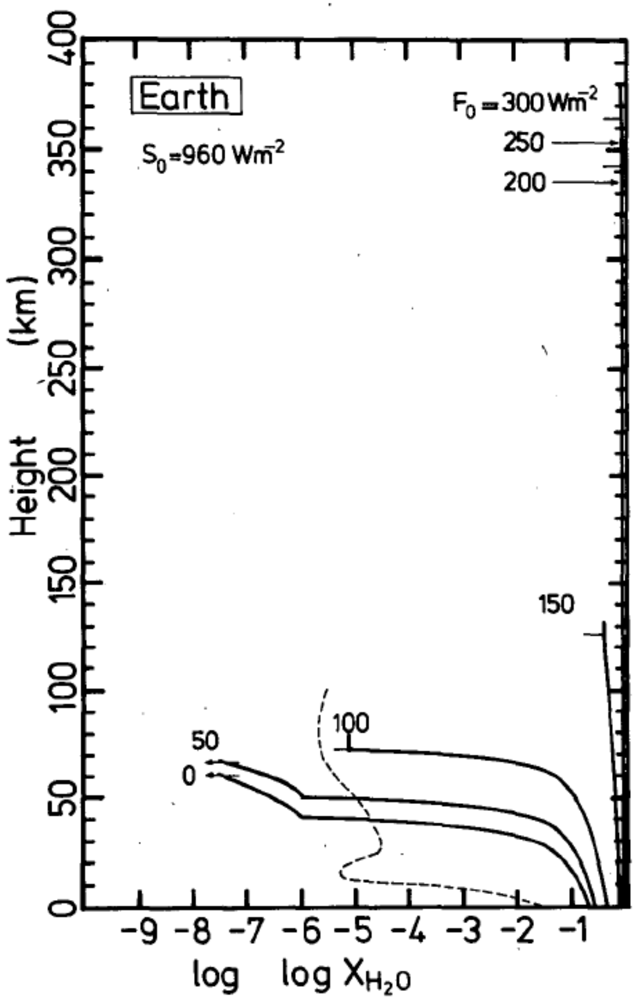
possible iron and silicate clouds in "substellar" atmospheres

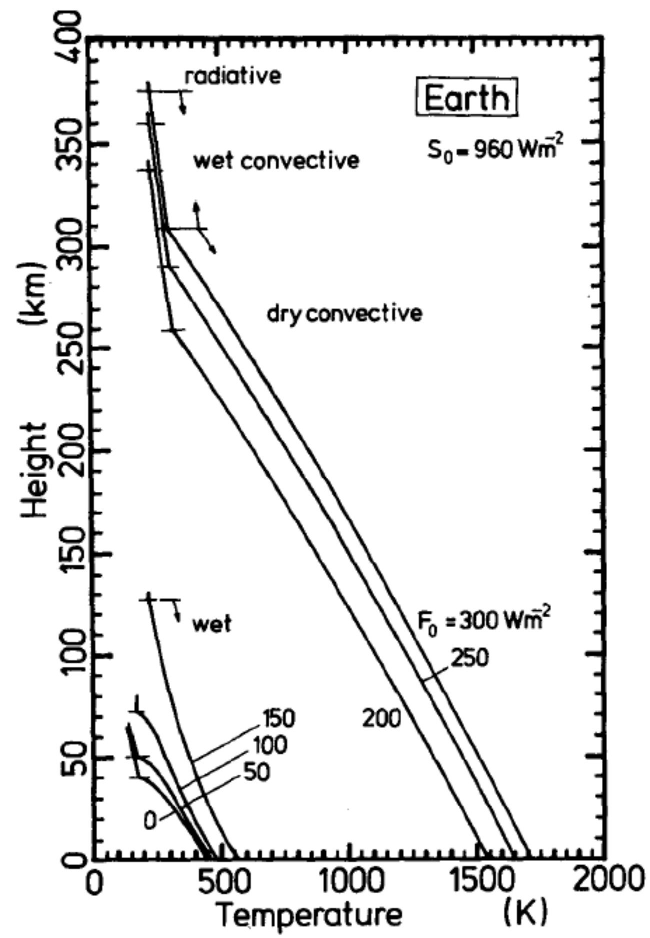


Burrow et al(1997)

Clouds in the atmospheres long long ago…

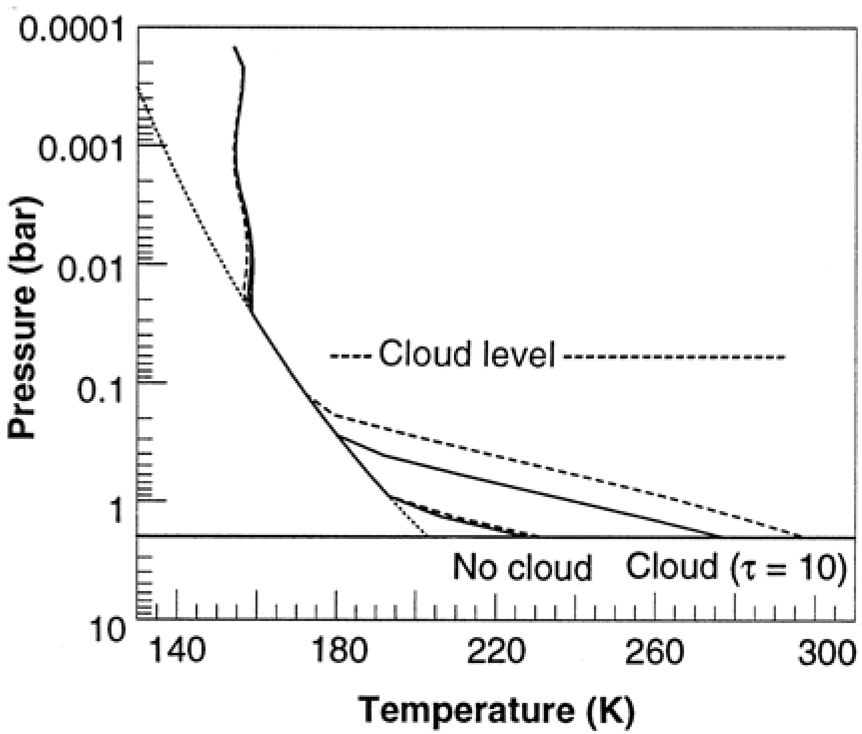
Almost pure water convection in the atmosphere of early Earth/Venus



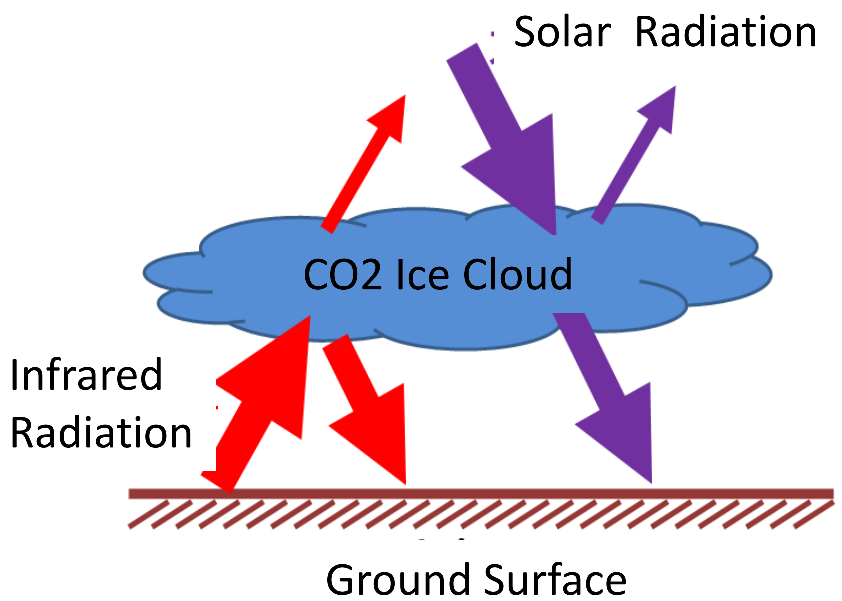


Abe and Matsui(1988)

Thick CO2 cloud in the atmosphere of Mars in its early history



Forget and Pierrehumbert (1997)

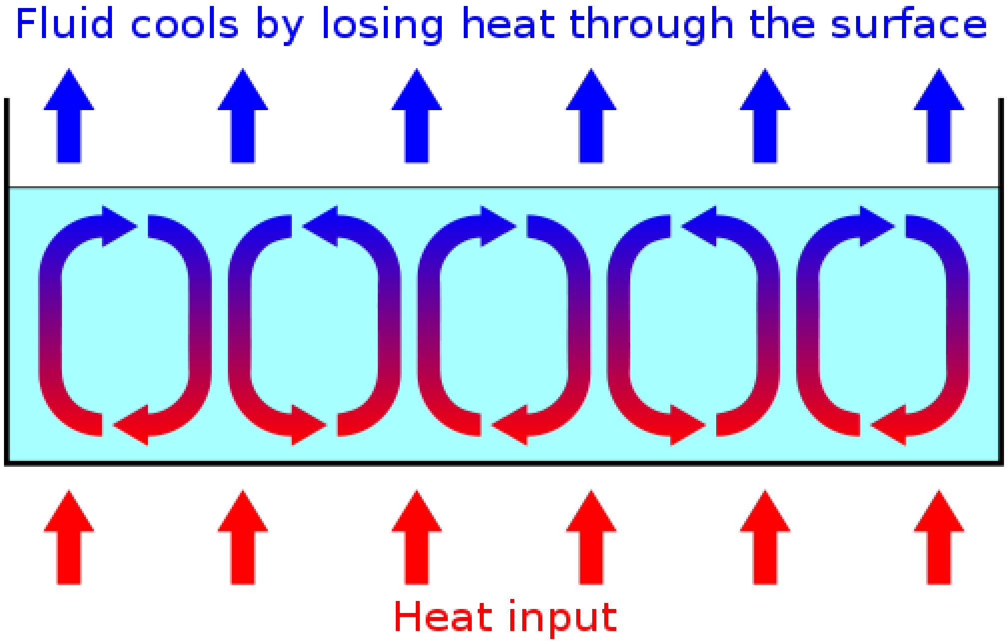


Pierrehumbert and Erlick(1998)

Basics of moist convection

(the earth's clouds in mind)

usual convection



http://en.wikipedia.org/wiki/B%C3A9nard_cells

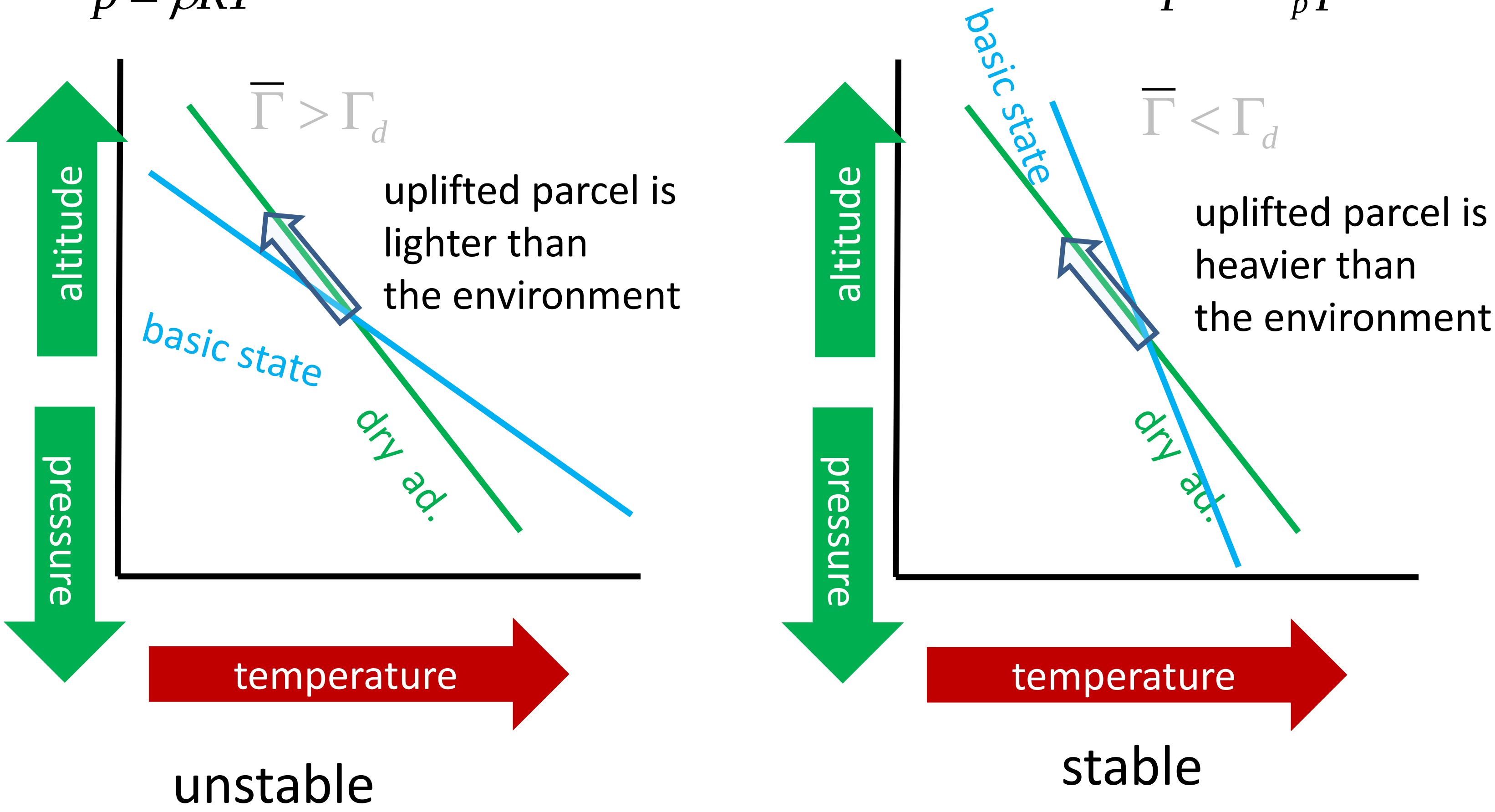
condition of convective instability: dry adiabatic lapse rate

$$c_p dT - \alpha dp = 0$$

$$p = \rho RT$$

$$c_p dT - \frac{RT}{p} dp = 0$$

$$\frac{dT}{dp} = \frac{R_n T}{c_p p} \equiv \Gamma_d$$



Moist adiabatic lapse rate

$$c_p dT - \alpha dp = d'Q$$

$$\varepsilon \equiv \mu_v / \mu_n$$

$$q = \varepsilon \cdot e_s / p$$

$$c_p dT - \frac{R_n T}{p} dp = -L dq$$

$$dq / q = de_s / e_s - dp / p$$

$$= L / (R_v T^2) \cdot dT - dp / p$$

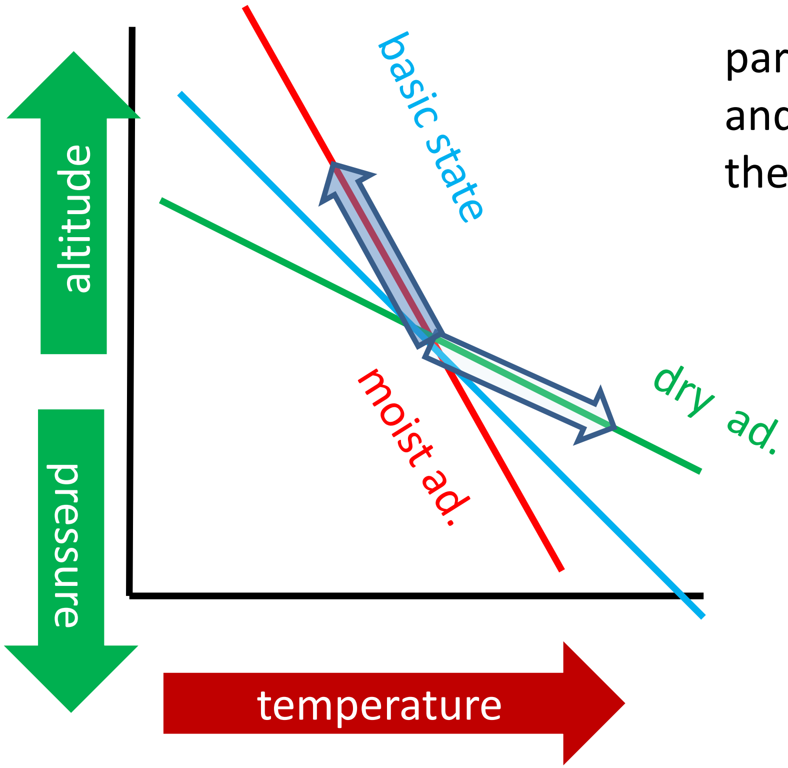
$$c_p dT - \frac{R_n T}{p} dp = -Lq \left(\frac{L}{R_v T^2} \cdot dT - \frac{dp}{p} \right)$$

$$\left(c_p + \frac{L^2 q}{R_v T^2} \right) \cdot dT = \left(R_n T + Lq \right) \cdot \frac{dp}{p}$$

$$\frac{dT}{dp} = \frac{R_n T}{c_p p} \cdot \left(1 + \frac{Lq}{R_n T} \right) \Bigg/ \left(1 + \frac{L^2 q}{c_p R_v T^2} \right) = \Gamma_d \cdot \left(1 + \frac{\varepsilon L e_s}{R_n T p} \right) \Bigg/ \left(1 + \frac{\varepsilon^2 L^2 e_s}{c_p R_n T^2 p} \right)$$

nonlinearity of moist convection (1) conditional instability

Asymmetry between upward and downward motion



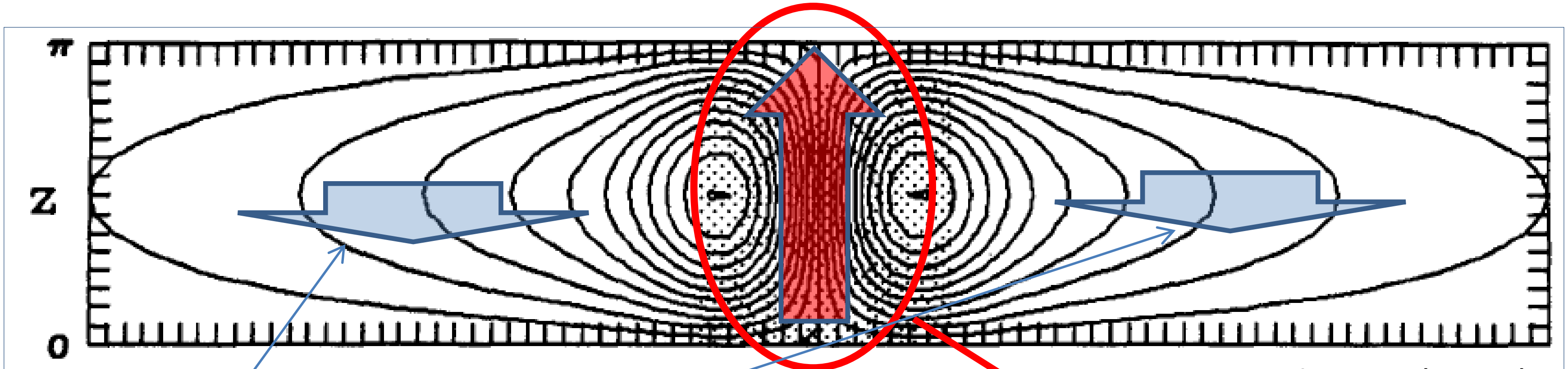
parcel moved upward is saturated and lighter than the environment, therefore unstable

parcel moved downward is unsaturated and lighter than the environment, therefore stable

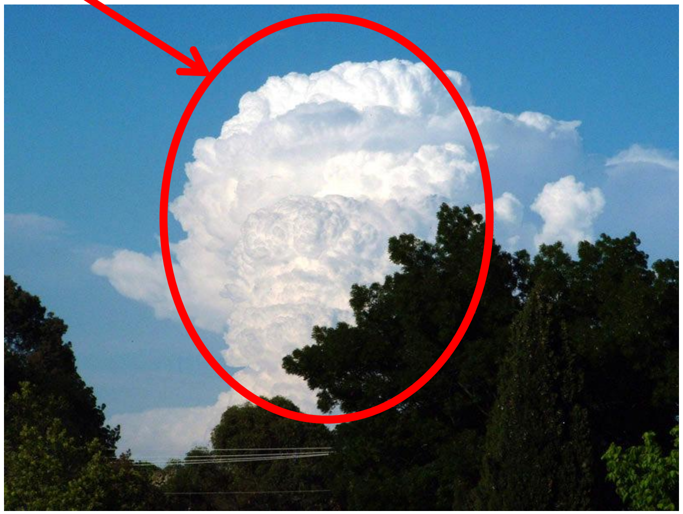
N.B. Basic state is assumed to be just saturated and clear (no cloud particles to evaporate) .

conditionally unstable

Asymmetric structure with conditional instability



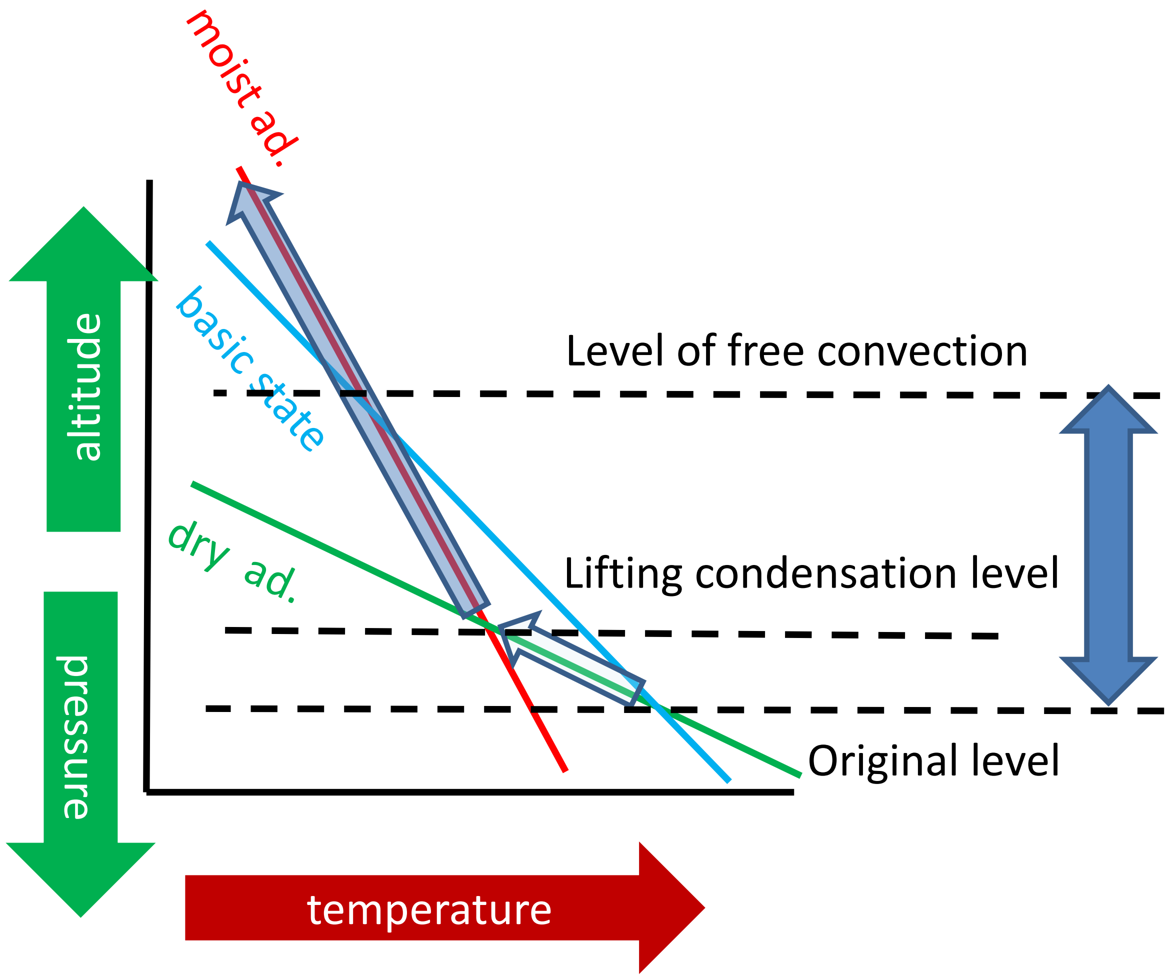
Bretherton(1987)



These weak downward motion are also very important.

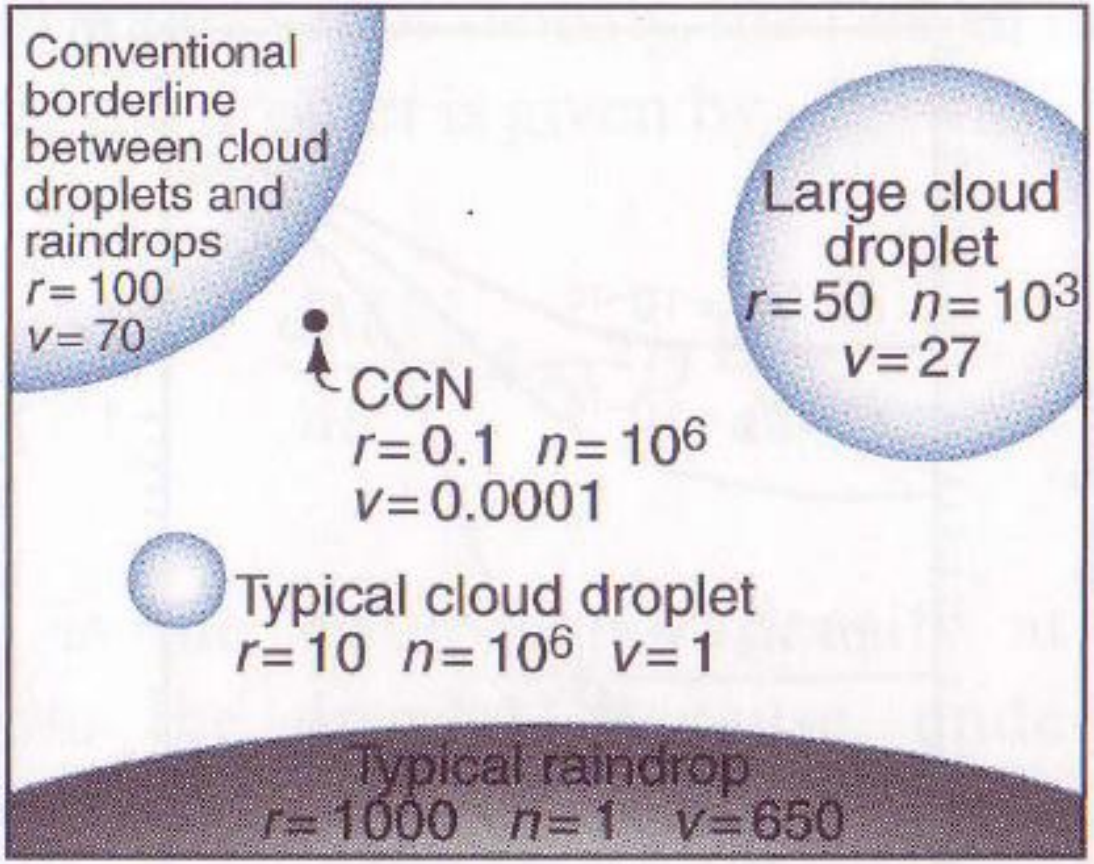
- it heats the wide area through adiabatic compression.
- large scale horizontal motion is accompanying it!

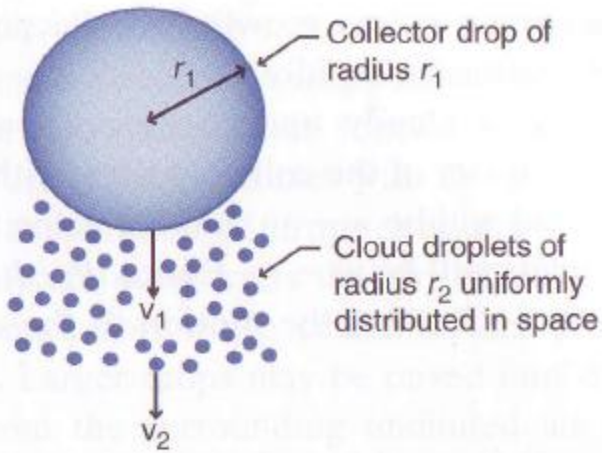
nonlinearity of moist convection
(2) potential instability



unsaturated parcel
must be lift-up
at least this depth
to become positively
buoyant

Cloud microphysics: a long way from molecule to raindrop

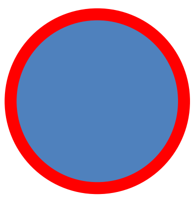




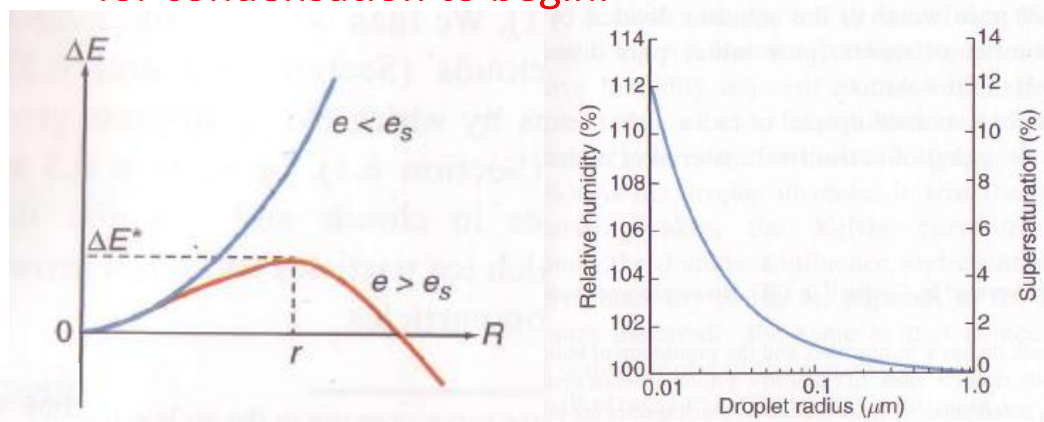
Wallace and Hobbs(2006)

Formation of cloud particle is difficult without “condensation nuclei”

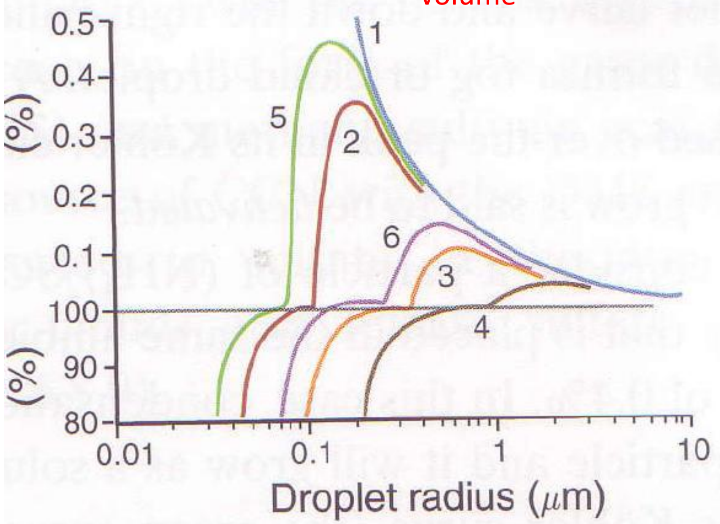
$$E = E_{volume} + E_{surface}$$
$$= (-) + (+)$$



With positive E, super saturation is necessary for condensation to begin.

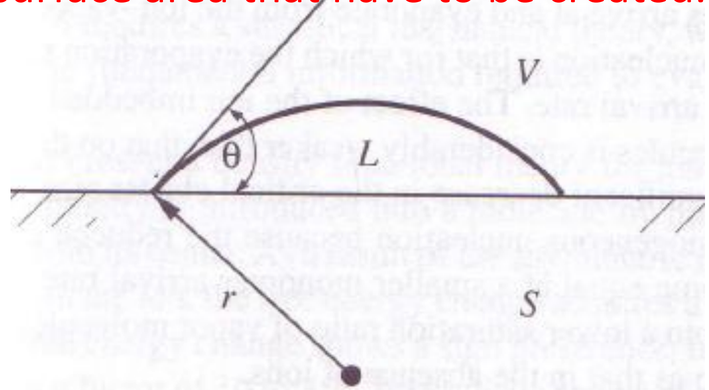


Solution lowers E_{volume}.



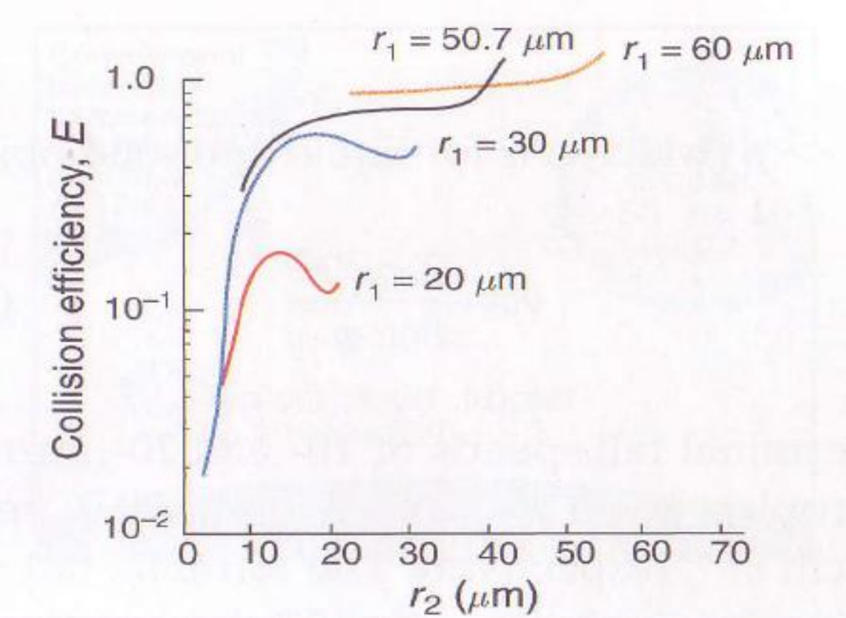
Wallace and Hobbs(2006)

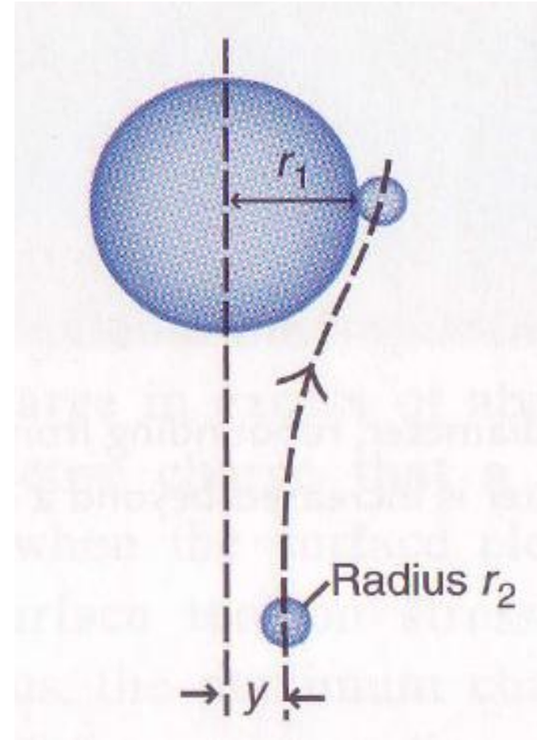
condensation on CCN can reduce the surface area that have to be created.

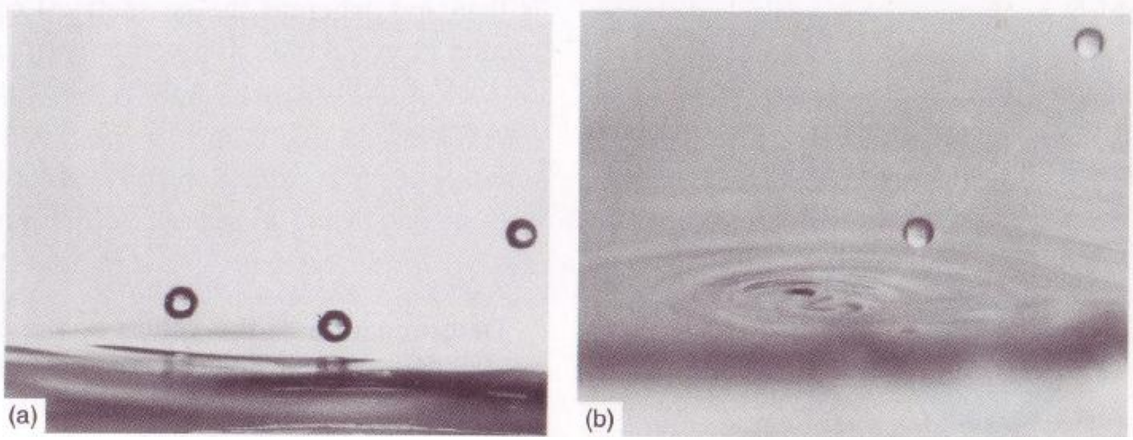


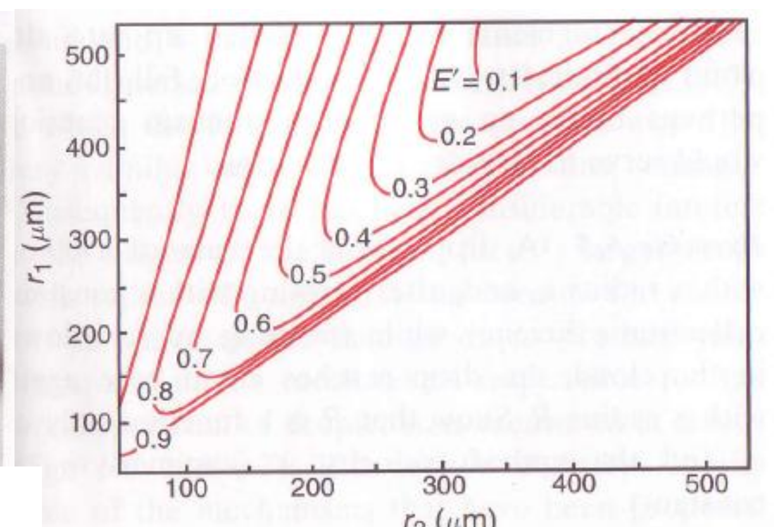
Seinfeld and Pandis(1998)

Collision Growth is not a “trivial” process









Wallace and Hobbs(2006)

governing equations for numerical model of moist convection

Fluid dynamics

$$\frac{du}{dt} = -c_p\Theta_0\frac{\partial\pi}{\partial x} + D(u),$$

$$\frac{dw}{dt} = -c_p\Theta_0\frac{\partial\pi}{\partial z} + b + D(w).$$

$$b \equiv g\left(\frac{\theta}{\Theta_0} + \left(\frac{m_n}{m_v} - 1\right)q_v - q_c - q_r\right)$$

$$\frac{\partial(\rho_0 u)}{\partial x} + \frac{\partial(\rho_0 w)}{\partial z} = 0$$

Thermodynamics

$$\frac{d\theta}{dt} + w\frac{\partial\Theta_0}{\partial z} = \frac{L}{c_p\Pi_0}(C - E_r) + D(\theta) + D(\Theta_0) + Q_{rad}$$

Budget equations for condensable components

$$\frac{dq_v}{dt} = -C + E_r + D(q_v),$$

$$\frac{dq_c}{dt} = +C - P_{rc} + D(q_c),$$

$$\frac{dq_r}{dt} = +P_{rc} - E_r - \frac{1}{\rho_0}\frac{\partial}{\partial z}(\rho_0 V_T q_r) + D(q_r).$$

Cloud micro physics

$$P_{rc} = P_{autoconv} + P_{collect}$$

$$P_{autoconv} = \frac{10^6\rho_0 q_c^3}{60(2q_c + 2.66\cdot 10^{-8}N_0/\rho_0 D_0)},$$

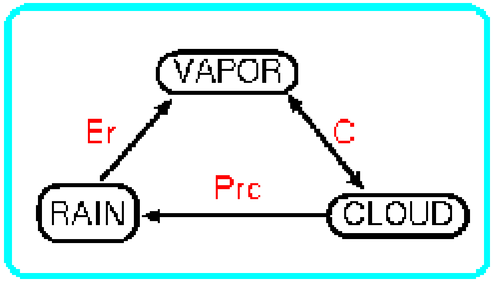
$$N_0 = 5.0\cdot 10^7$$

$$D_0 = 0.366$$

$$V_T = 12.2q_r^{1/8},$$

$$P_{collect} = 2.2q_c(\rho_0 q_r)^{7/8},$$

$$E_r = 4.85\cdot 10^{-2}(q_v^* - q_v)(\rho_0 q_r)^{0.65}$$



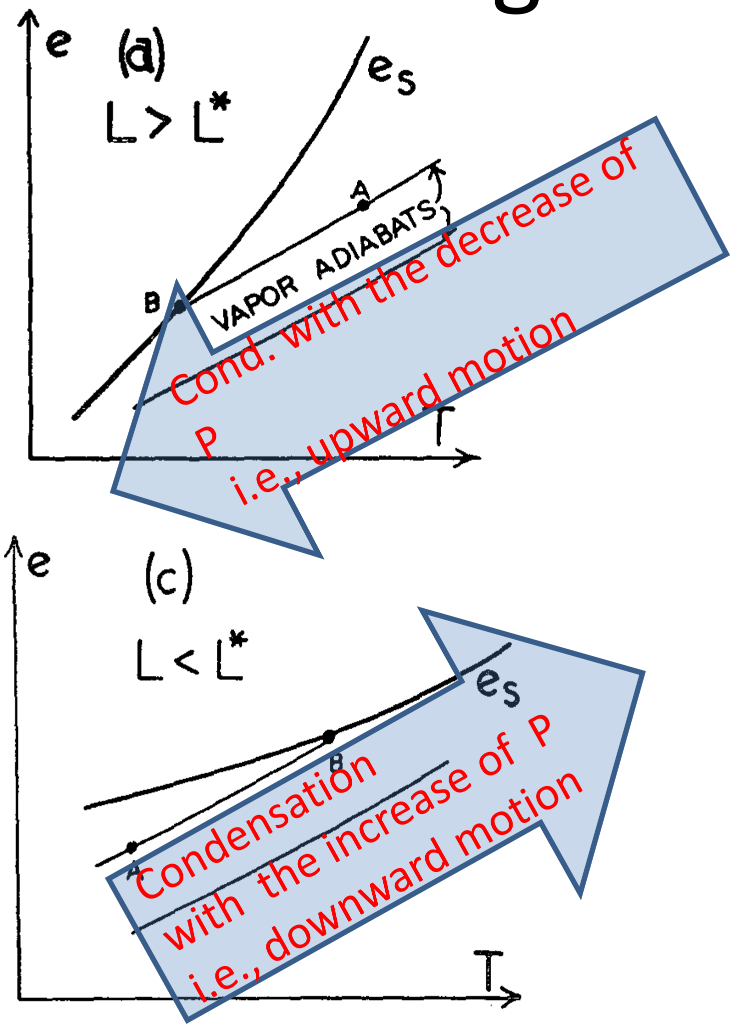
Re-examination of moist convection

(planetary clouds in mind)

Issues to be re-examined

- Condensable and non-condensable components can be different from *water vapor* and *air.*
  - Does condensation only in upward motion?
  - Condensable component may be heavier (i.e., having larger molecular weight) than non-condensable component.
- Large-degree of super-saturation may be necessary to begin condensation.
- Major component may condense.

Sign of vertical motion resulting in condensation



McDonald(1964)

$$\frac{de_s}{dT} = \frac{L}{\Delta v_v \cdot T} = \frac{L}{R_v T^2} e_s$$

$$\frac{de}{dT} = \frac{n_v}{n_n} \cdot \frac{dp}{dT} = \frac{n_v}{n_n} \cdot \frac{c_{pn}}{R_n} \frac{p}{T}$$

$$= \frac{c_{pn}}{R_n} \cdot \frac{e}{T} = \frac{L^*}{R_v T^2} e$$

$$L^* \equiv \frac{c_{pn}}{R_n} R_v T$$

Condensation occurs with upward motion for all planet

$$L > L^* \equiv \frac{c_{pn}}{R_n} R_v T \Leftrightarrow S^* > C_{pn}$$

substance	T[K]	S* [J/mol K]
H2O	270	168
NH3	250	92
CH4	100	86
C2H6	90	160
CO2(sublimation)	190	125
Fe	1800	200
MgSiO3	2000	225

$$S^* \equiv \frac{LR}{R_v T} = \frac{l}{T} > \frac{c_{pn} R}{R_n} = C_{pn}$$

$$C_{pn} \approx (2.5 \sim 3.5)\, R$$
$$\approx 20 \sim 30\, [J/mol \cdot K]$$

Condensation occurs in upward motion in all (maybe) planetary atmospheres

Effect of molecular weight on the density of saturated parcel

$$\rho = \rho_n + \rho_v = \frac{\mu_n p_n}{RT} + \frac{\mu_v p_v}{RT} = \frac{\mu p}{RT} \qquad \mu \equiv \mu_n \frac{p_n}{p} + \mu_v \frac{p_v}{p}$$

$$\left(\frac{\rho'}{\rho}\right)_p = \left(\frac{\mu'}{\mu}\right)_p - \frac{T'}{T} = \left(\frac{T}{\mu}\left(\frac{d\mu}{dT}\right)_p - 1\right)\cdot\frac{T'}{T} \qquad e_s = p\cdot\frac{\mu}{\mu_v} r_v^*$$

$$\left(\frac{d\mu}{dT}\right)_p = \frac{\mu_n}{p}\frac{d}{dT}(p - e_s) + \frac{\mu_v}{p}\frac{d}{dT}e_s = \frac{\mu_v - \mu_n}{p}\frac{d}{dT}e_s$$

$$= \frac{\mu_v - \mu_n}{p}\frac{L}{RT^2}e_s = (\mu_v - \mu_n)\frac{L}{RT^2}\frac{\mu}{\mu_v}r_v^* = \left(1 - \frac{\mu_n}{\mu_v}\right)\frac{Lr_v^*}{RT^2}\mu$$

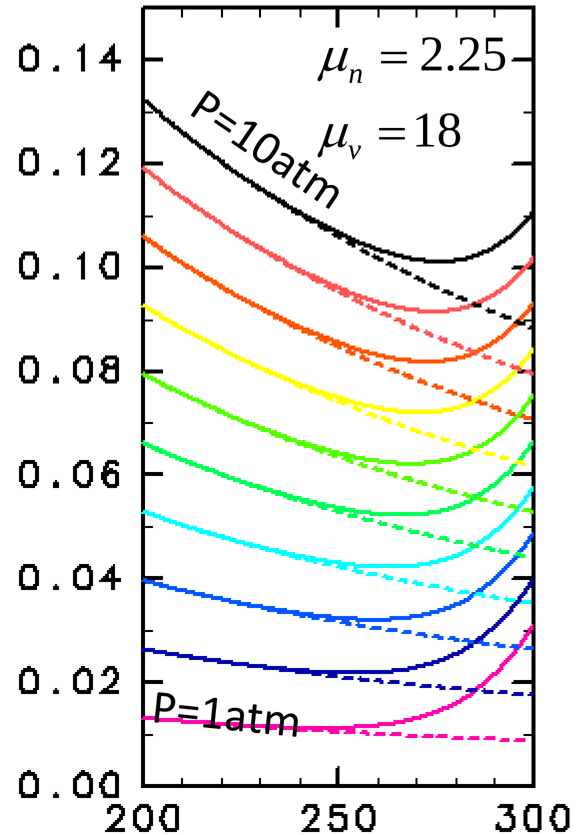
$$\frac{T}{\mu}\left(\frac{d\mu}{dT}\right)_p - 1 = \left(1 - \frac{\mu_n}{\mu_v}\right)\frac{Lr_v^*}{RT} - 1$$

Effect of molecular weight on the density of ascending parcel

$$\left(\frac{\rho'}{\rho}\right)_p = \left(\frac{\mu'}{\mu}\right)_p - \frac{T'}{T} = \left[\left(1-\frac{\mu_n}{\mu_v}\right)\cdot\frac{L}{RT}r_v^{\ *} - 1\right]\cdot\frac{T'}{T}$$

If the condensable component is heavier than the non-condensable component, and its mixing ratio and/or the latent heat of condensation is large enough (i.e., the saturation vapor pressure depends strongly on the temperature), the ascending warmer parcel is heavier than the colder air in the environment!

Density of Jovian air saturated with water vapor



Nakajima et al (1998)

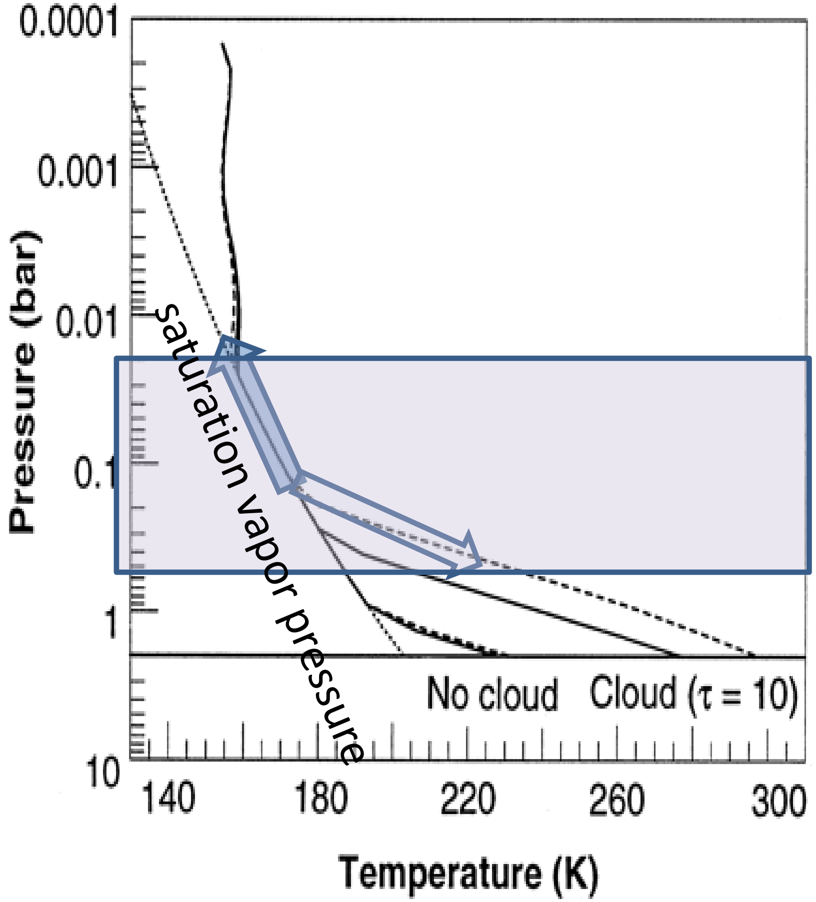
The effect of molecular weight can be quite significant in Jovian planetary atmospheres

mixing ratios of condensable component						
	critical value	Jupiter	Saturn	Uranus	Neptune	solar system standard
H2O	0.057	?	?	?	?	0.015
NH3	0.104	0.004	0.002	?	?	0.002
CH4	0.112	(0.048)	(0.072)	0.368	0.24	0.006

Guillot (1995)

major component condensation

$\rho = \rho(p,T) = \rho(p,T(p)) = \rho(p)$



Forget and Pierrehumbert(1997)

- P and T are constrained along saturation vapor pressure P=P(T).
- In a plain view, the saturated layer is *neutral* because the fluid is *barotropic,* so that vorticity is conserved.
- Details of cloud microphysics could be critical.
  - The weight of cloud particles can significantly affect buoyancy.
  - Slight departure from saturation vapor pressure may affect buoyancy.
  - Cloud particles affects temperature change within downward motion.

Quicklook of moist convection numerically simulated in the condition of planetary atmospheres (more or less)

The Earth

Plenty of water cloud.

Ocean covers 70%.

Water vapor is lighter than the dry air.

Nucleation is easy (We know it!).

with full-set of cloud physics

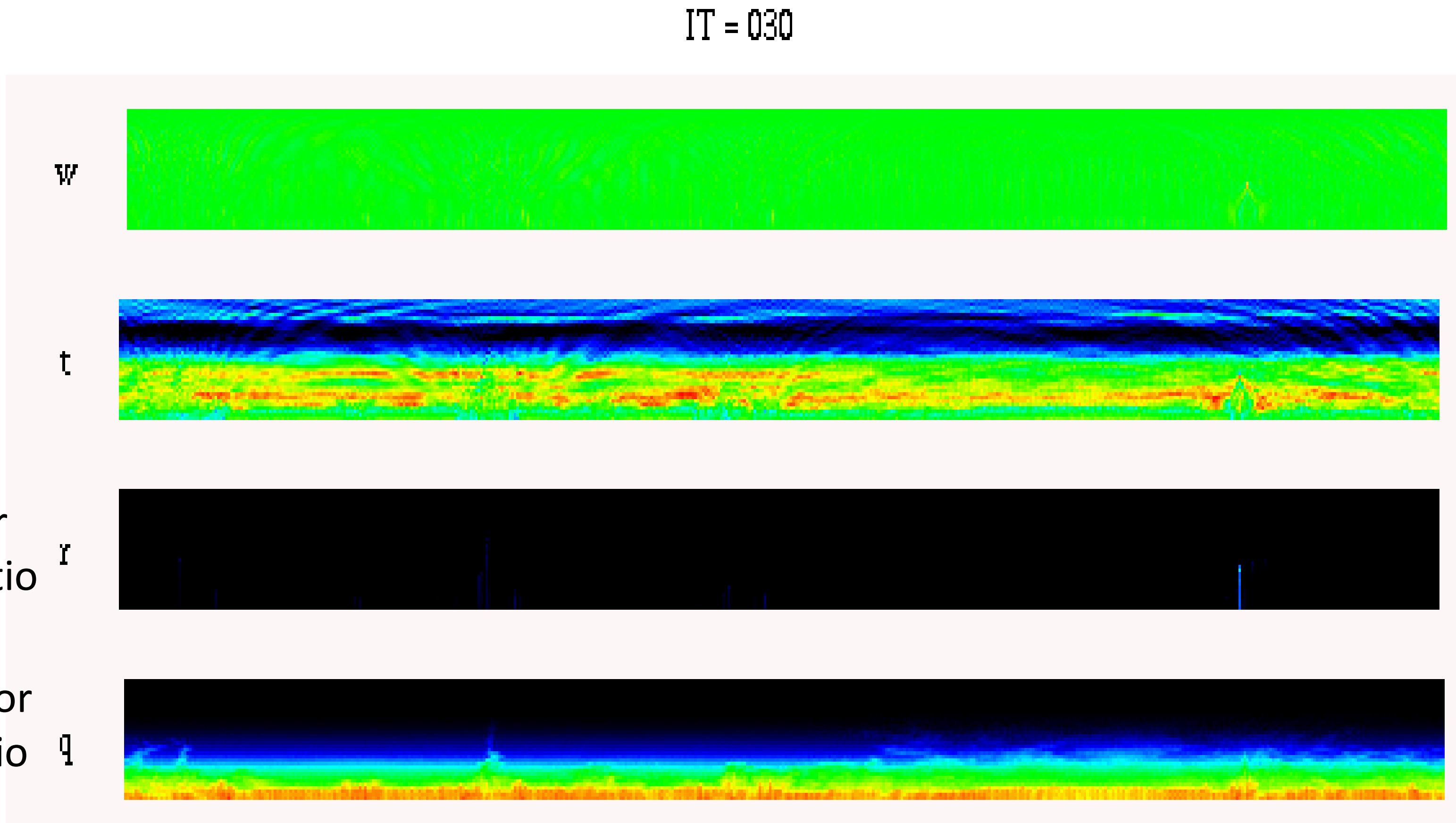
Life cycle of individual convective cloud
The effect of cloud (e.g. temperature change) propagates as waves.

vertical velocity

temperature anomaly

rain water mixing ratio

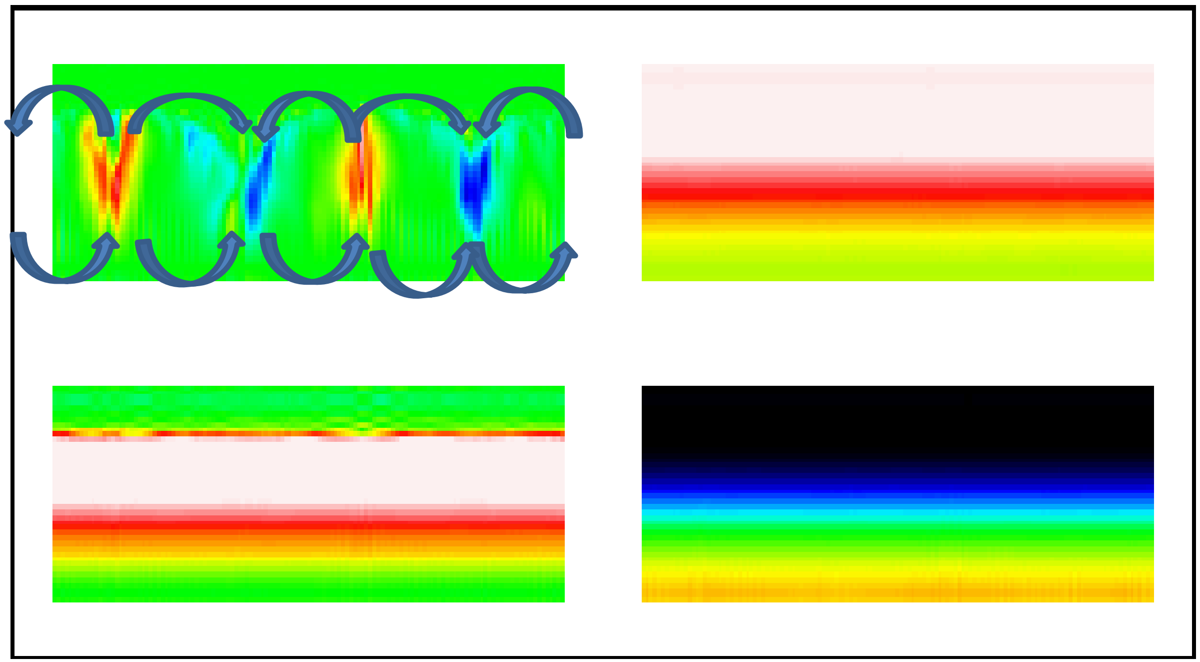
water vapor mixing ratio



Without precipitation processes, moist convection is not very different from Bernard convection (Miso soup)

vertical velocity

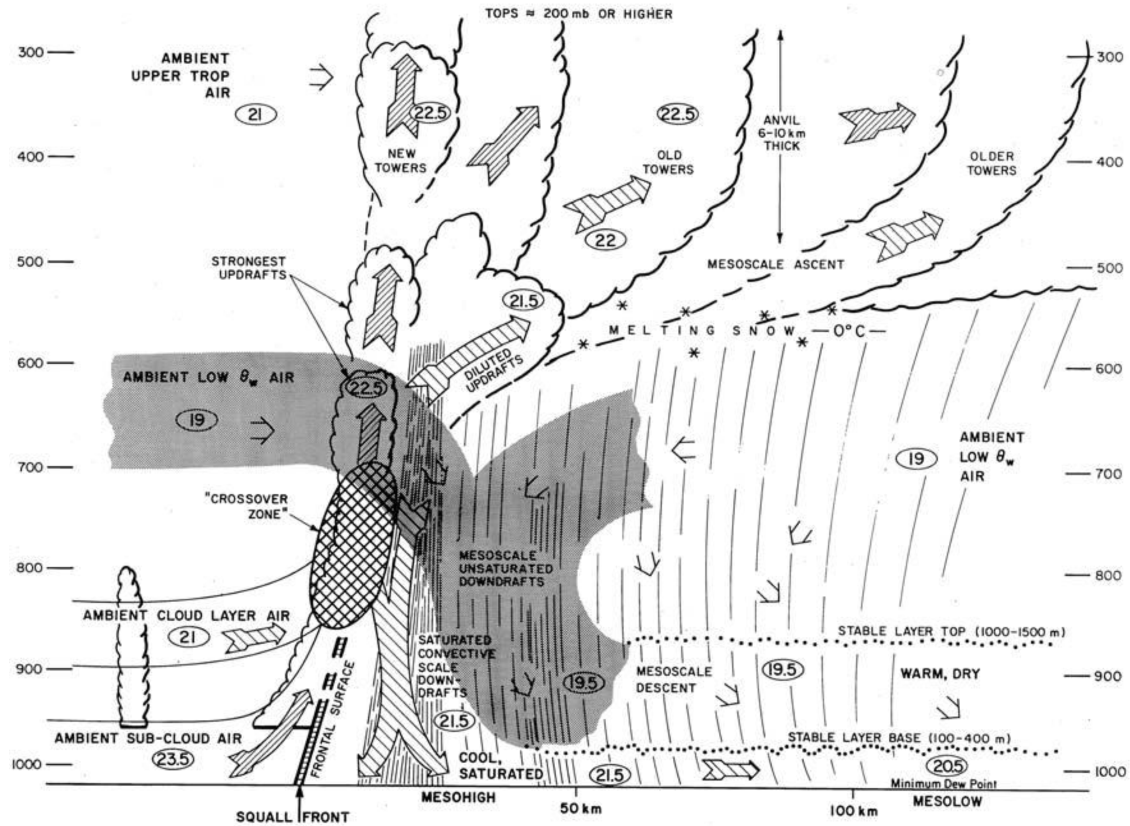
temperature anomaly



cloud mixing ratio

water vapor mixing ratio

Convective clouds tends to form as groups owing to the formation of rain



Tao and Moncrieff(2009)

http://earth.jsc.nasa.gov/sseop/EFS/lores.pl?PHOTO=STS41C-40-2130

http://earth.jsc.nasa.gov/sseop/EFS/photoinfo.pl?PHOTO=STS51G-46-5

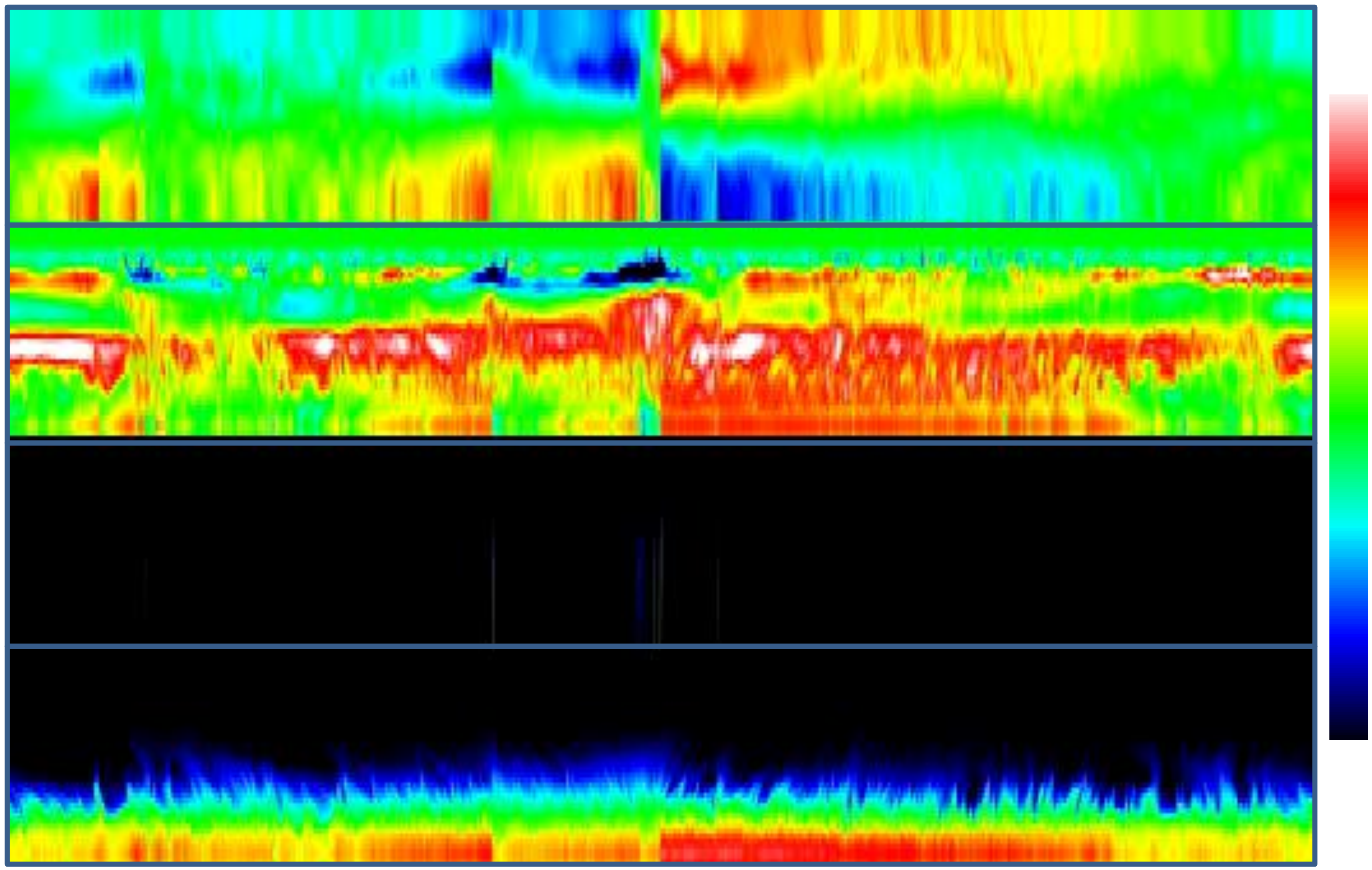
Horizontal scale of motion associated with cloud can have planetary scale.

Horizontal wind

Potential Temperature Anomaly

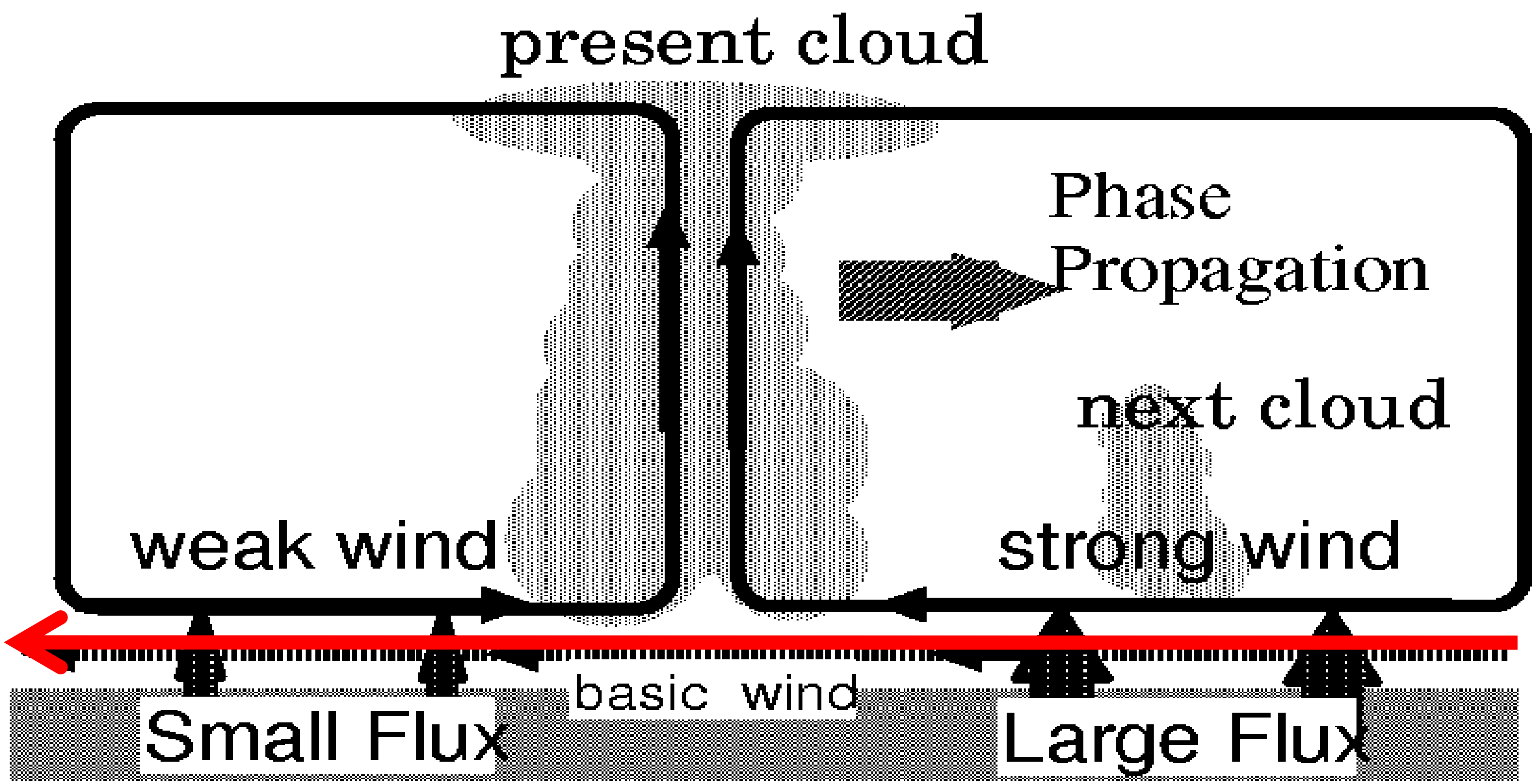
Rain water Mixing ratio

Water vapor Mixing ratio



domain : Zoomed from 65,536km to 128km

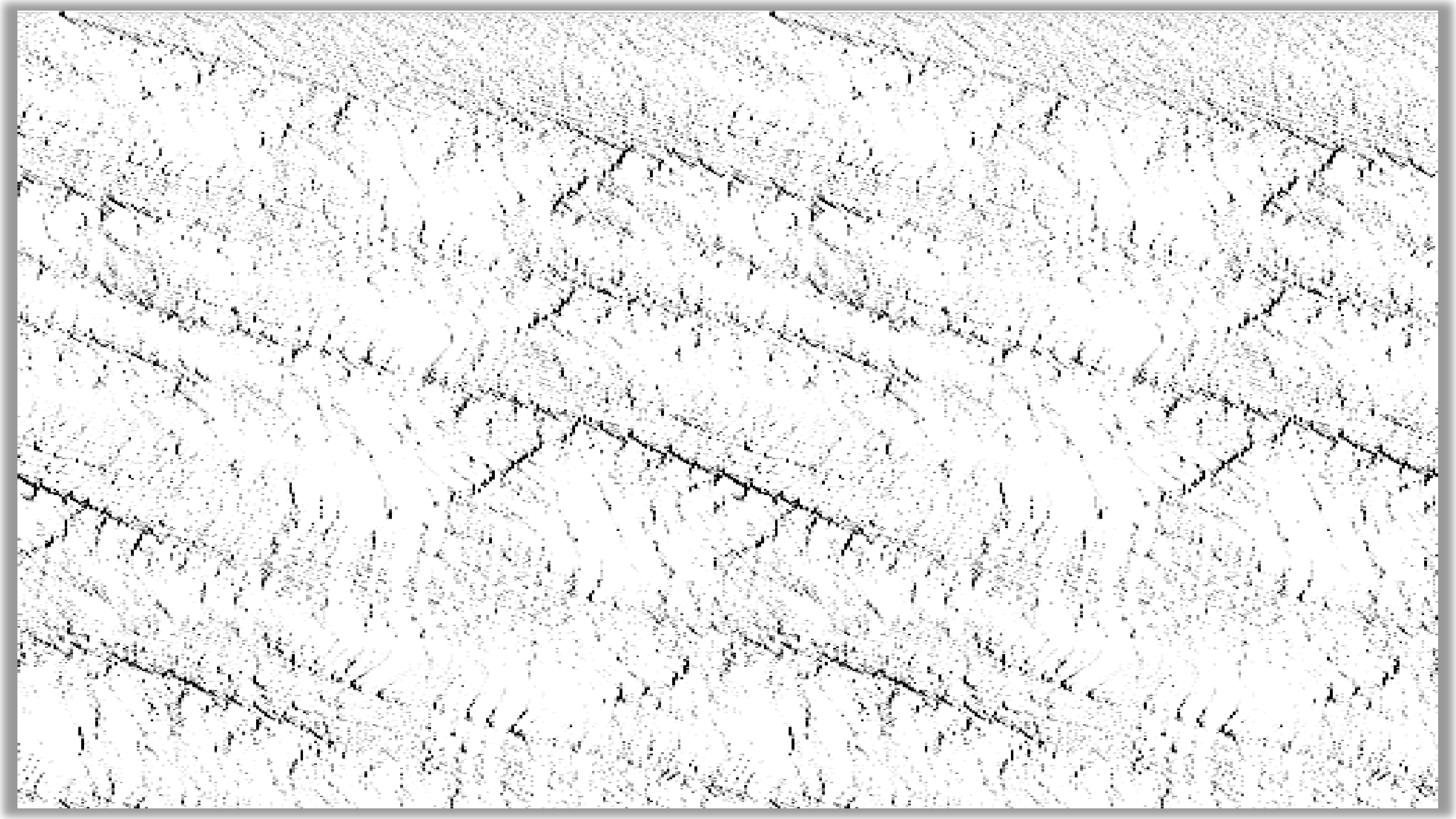
wind-induced surface heat exchange



In the presence of basic wind, convective activity propagates by the asymmetry of surface flux.

Organization affected by asymmetry of boundary condition

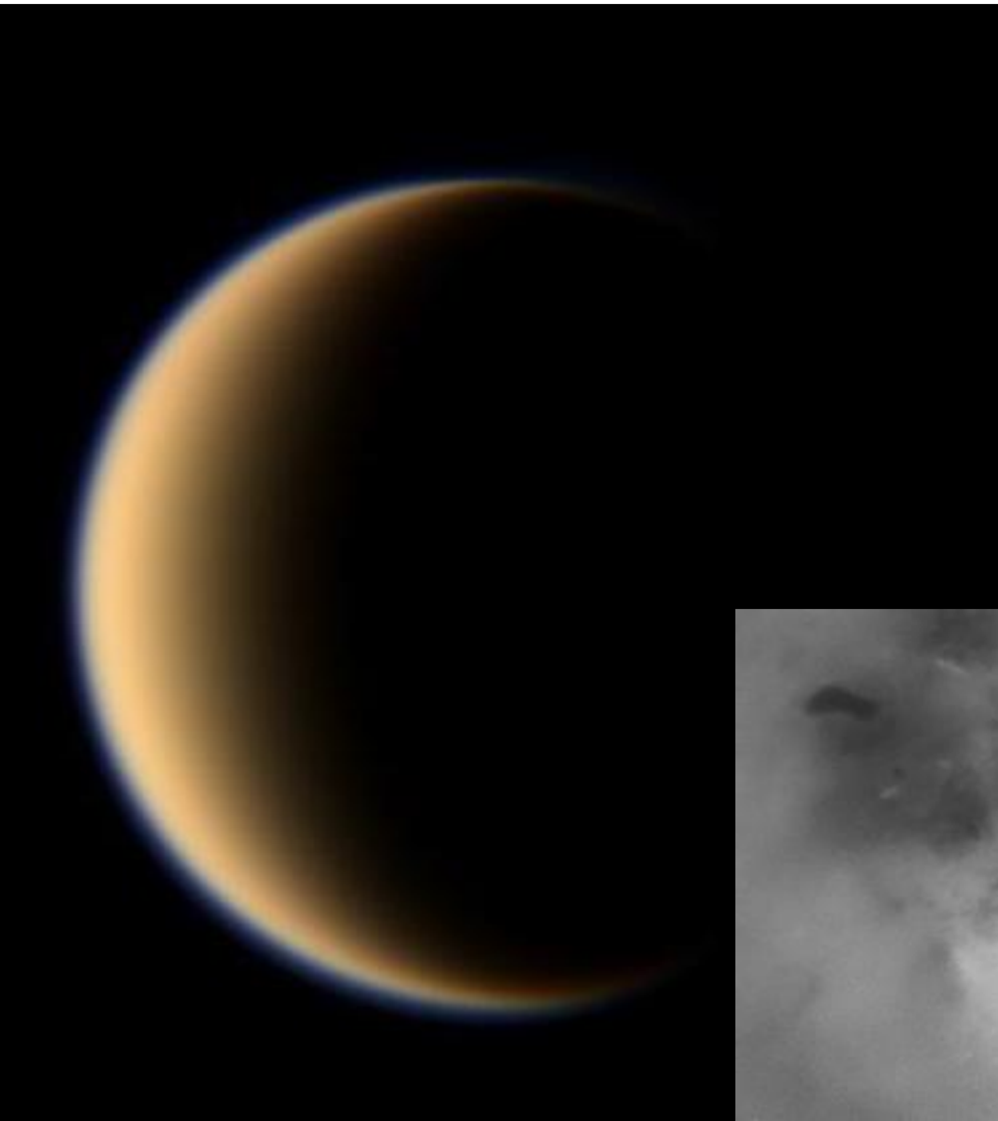
Rainfall intensity propagating pattern is prominent.

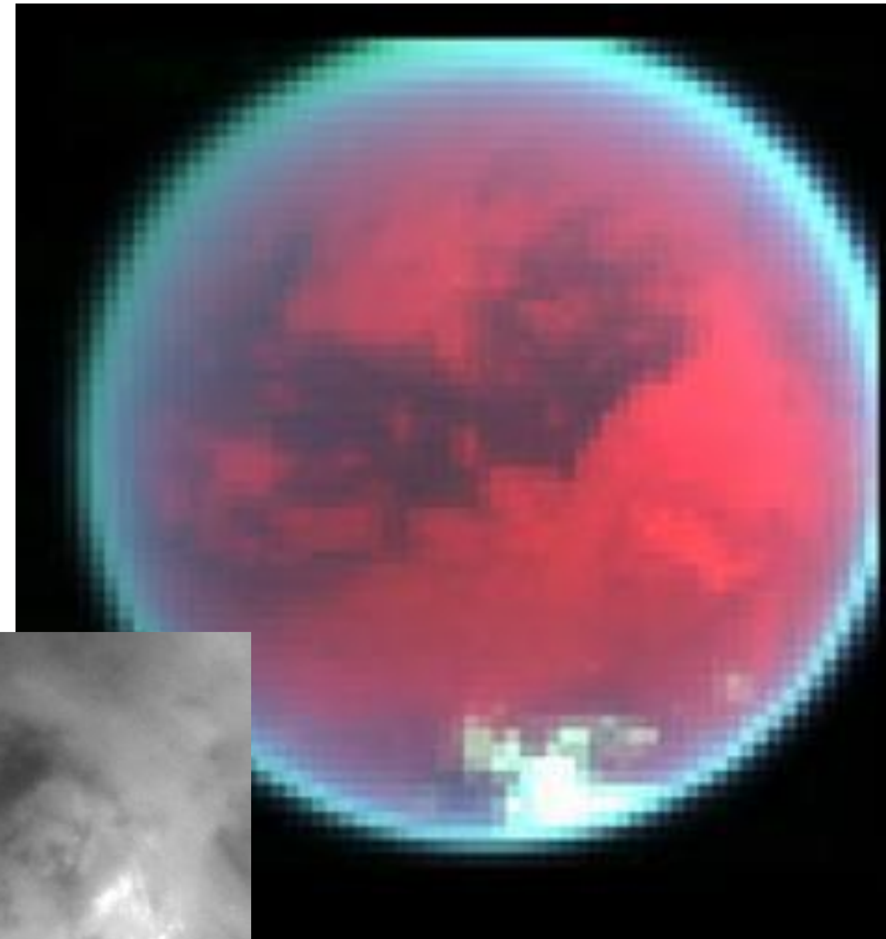


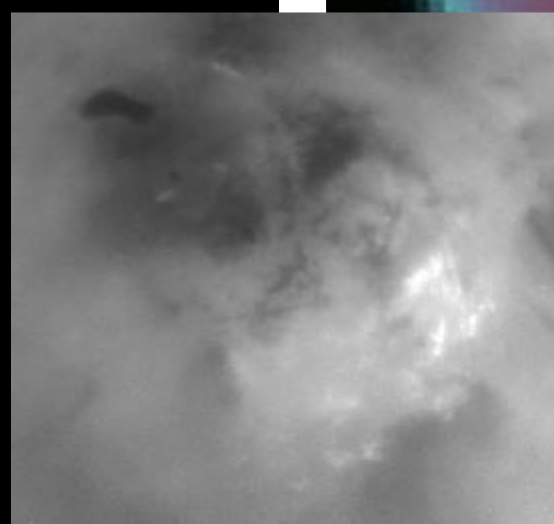
Time 80 days

Space (horizontal) 32,768km × 2 cycles

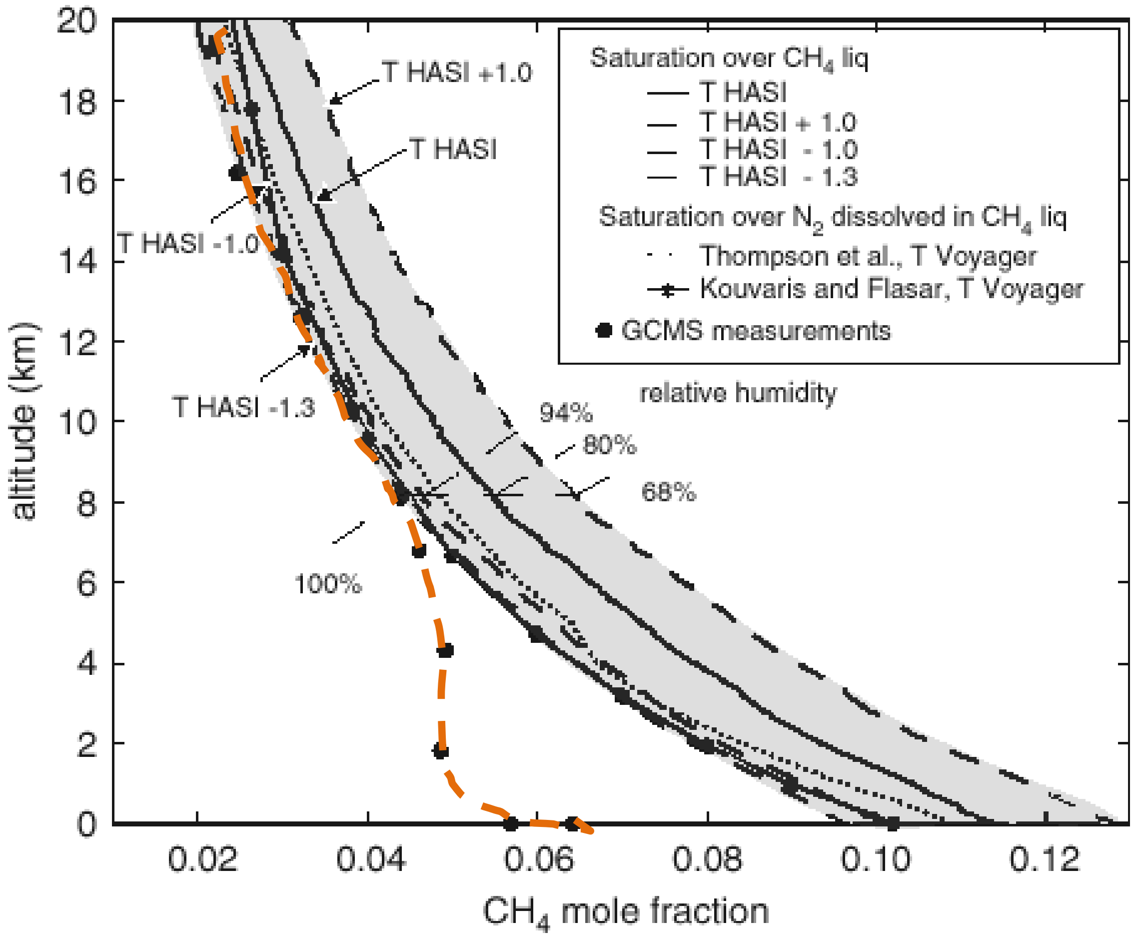
Methane clouds on Titan







Methane distribution in lower atmosphere of Titan



Atreya et al(2006)

saturated from 8-14 km.

significantly unsaturated below 8km.

Any convective cloud is possible?

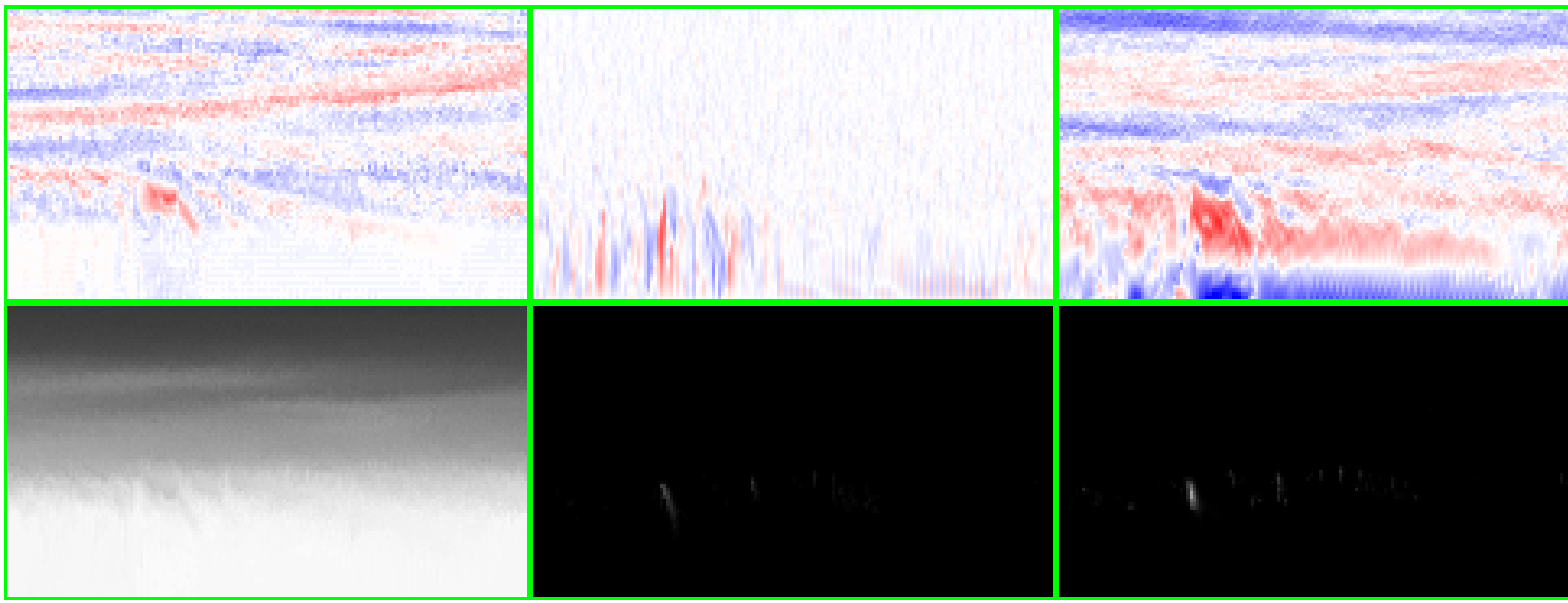
Are there good aerosols?

How will be the methane “hydrology” like?

simulated cloud

beginning of active convective cloud

temperature(±1K)　w(±4m/s)　u(±4m/s)



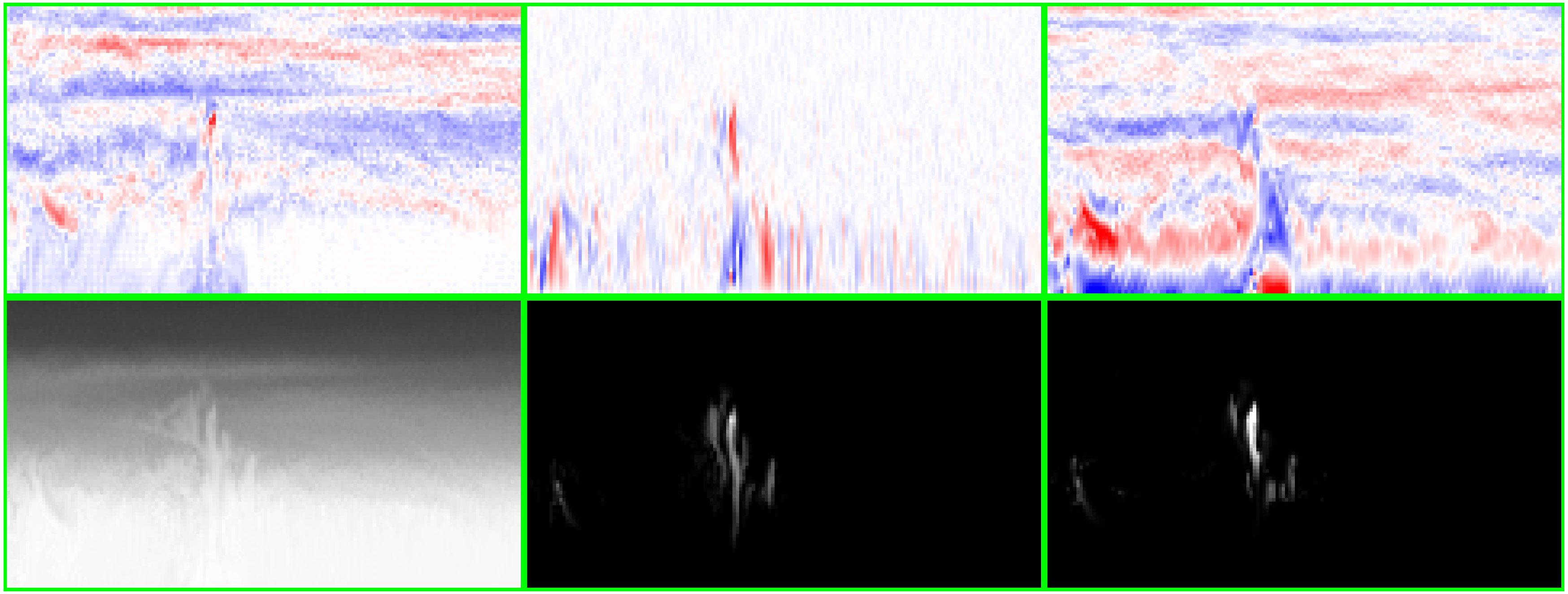
mixing ratio： vapor(0-0.03) rain(0-0.004) cloud(0-0.016)

横80km　縦20km

9hours later

- rainfall occurs, but mostly evaporates before reaching to the ground surface

temperature(±1K)　　w(±4m/s)　　u(±4m/s)



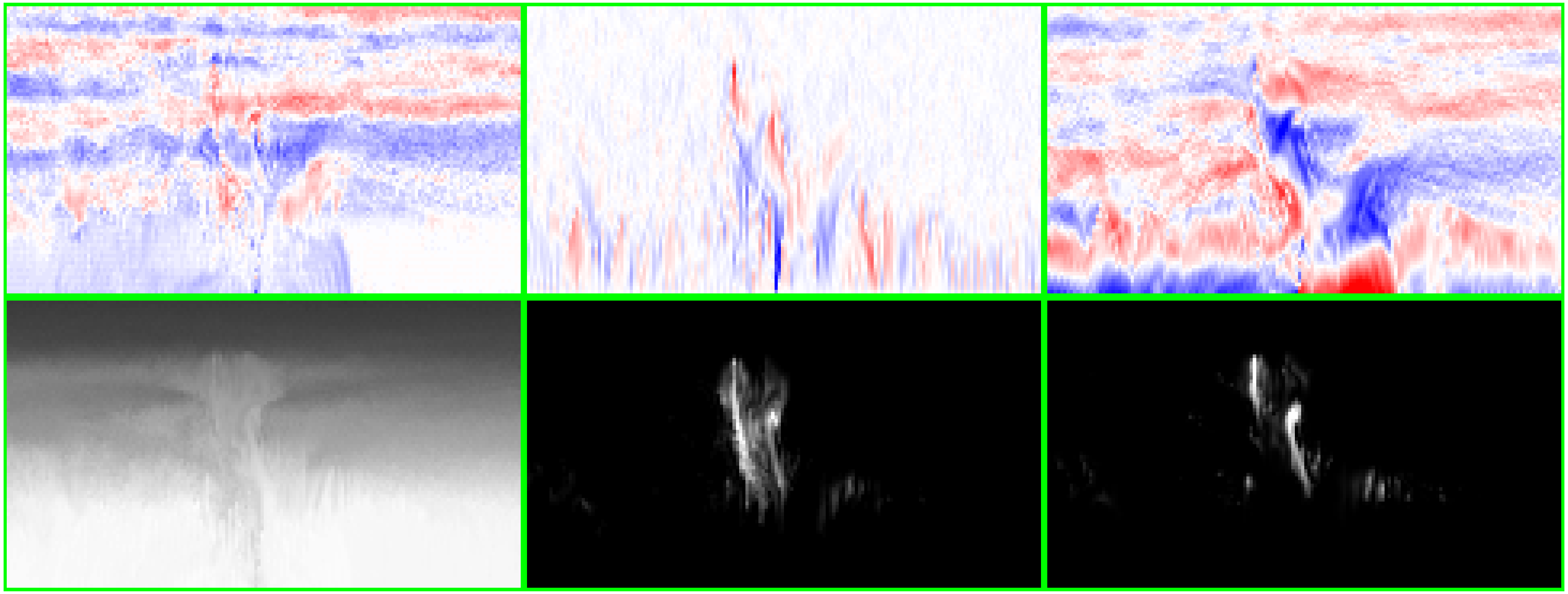
mixing ratio： vapor(0-0.03) rain(0-0.004) cloud(0-0.016)

横80km　縦20km

14hours later

- cloud top is 16km. Cold pool near the surface resulting in successive cloud formation.

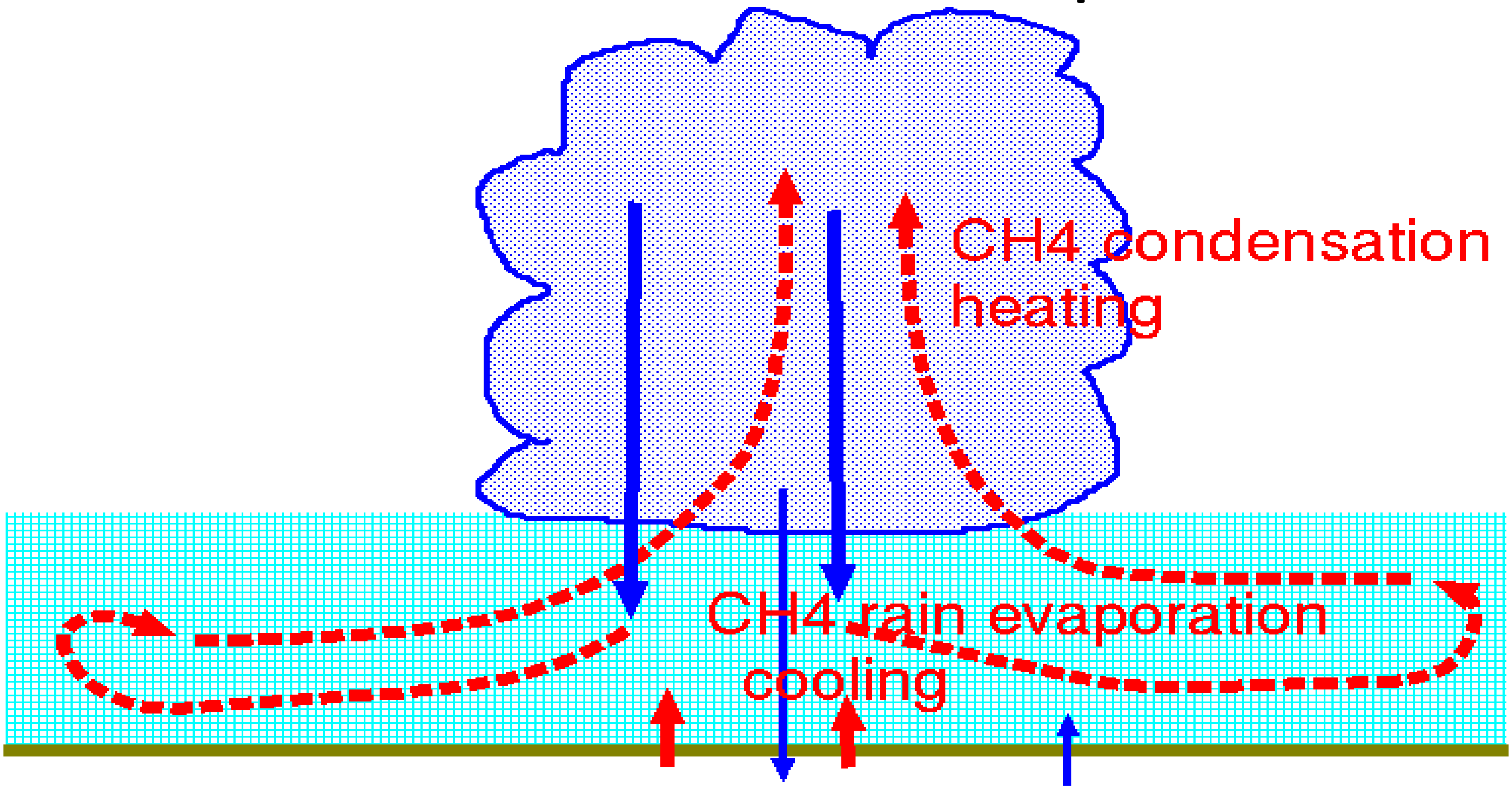
temperature(±1K)　　w(±4m/s)　　u(±4m/s)



mixing ratio： vapor(0-0.03) rain(0-0.004) cloud(0-0.016)

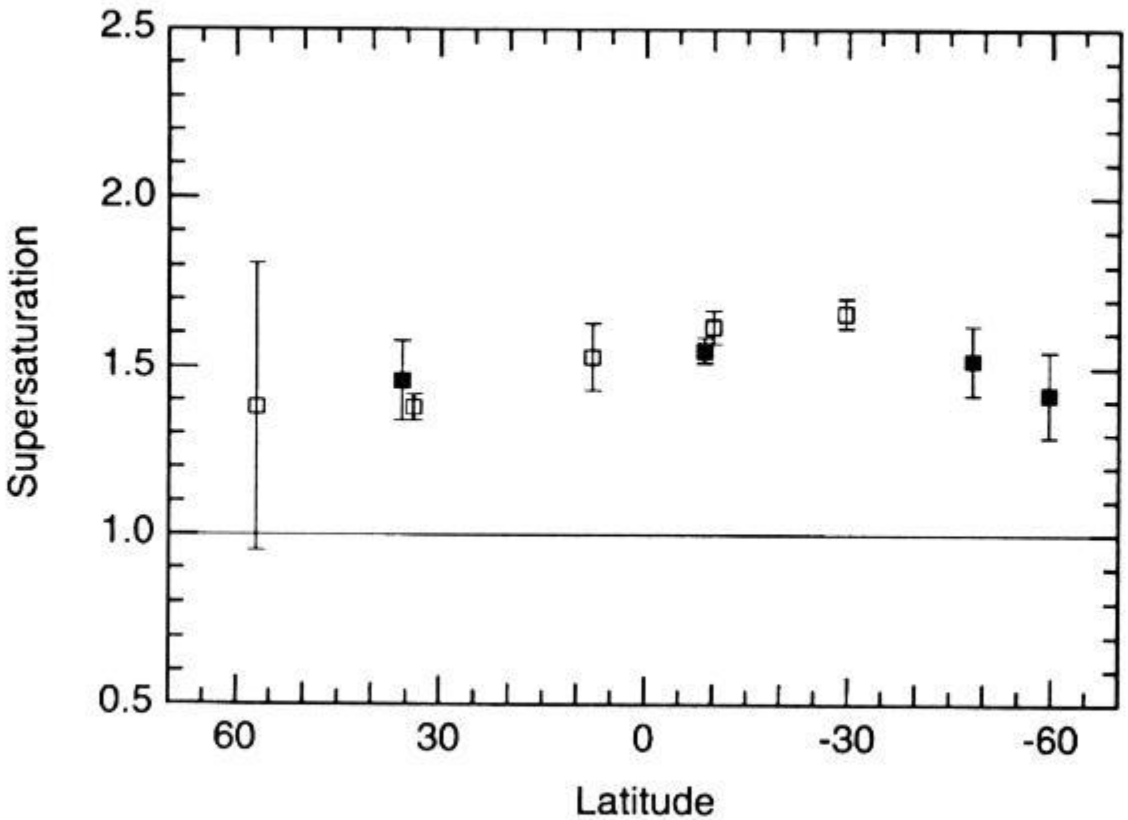
横80km　縦20km

Possibly large contribution to vertical heat transport



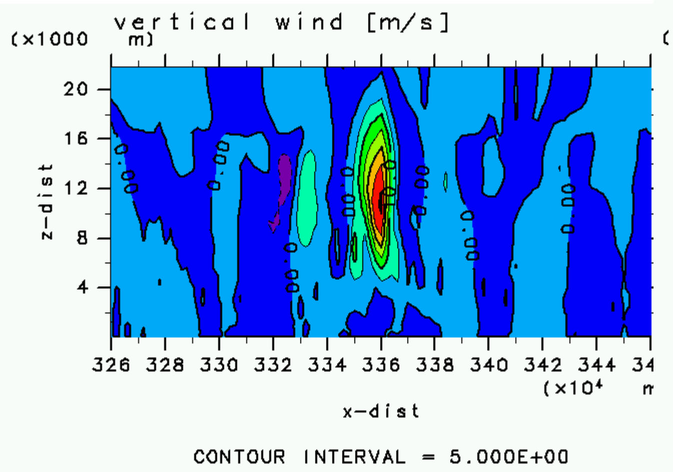
Precipitation and evaporation are weak.

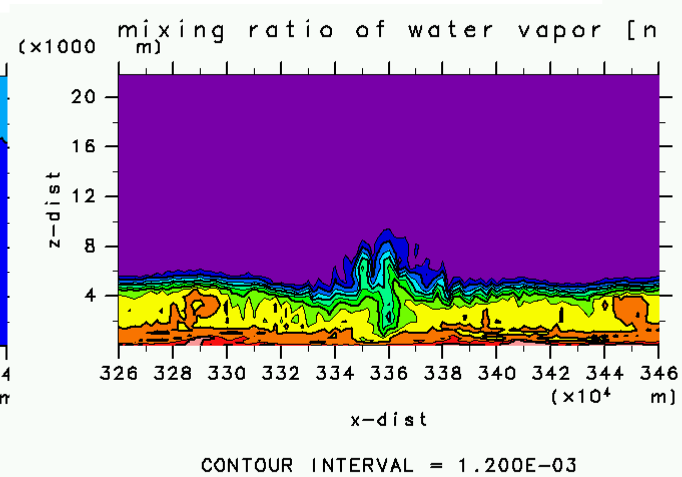
Large degree of super saturation at other part of the atmosphere?

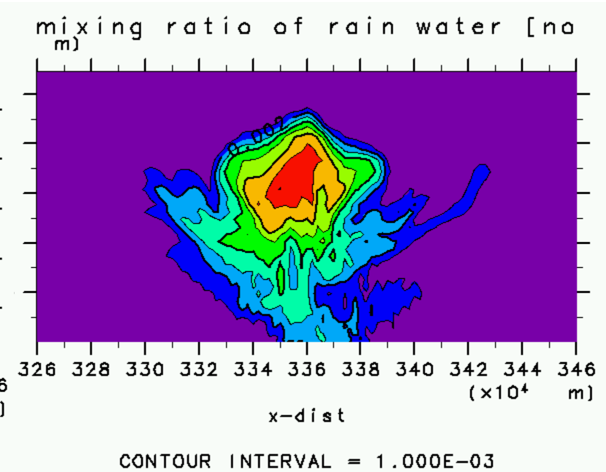


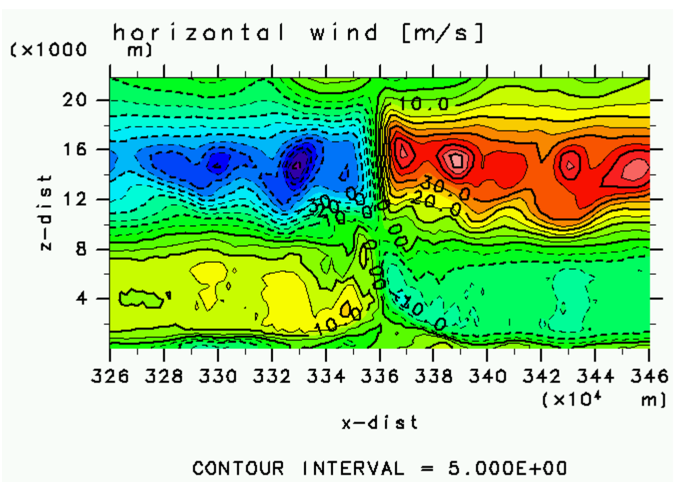
Flasar(1998)

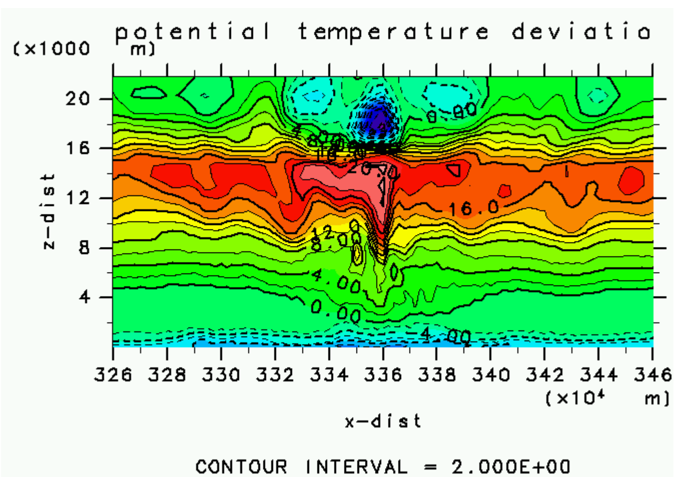
With large threshold for condensation (earth-like composition)



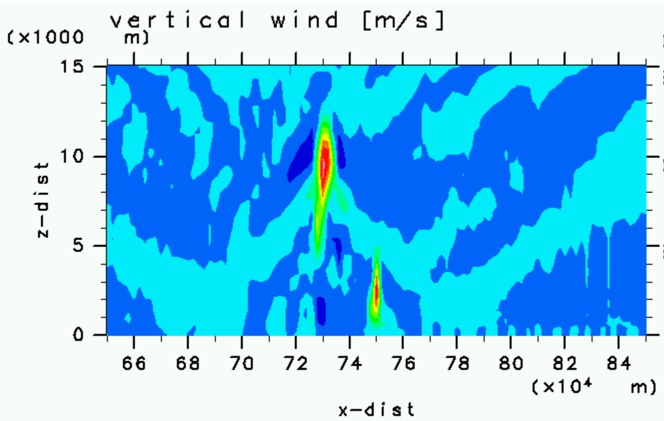


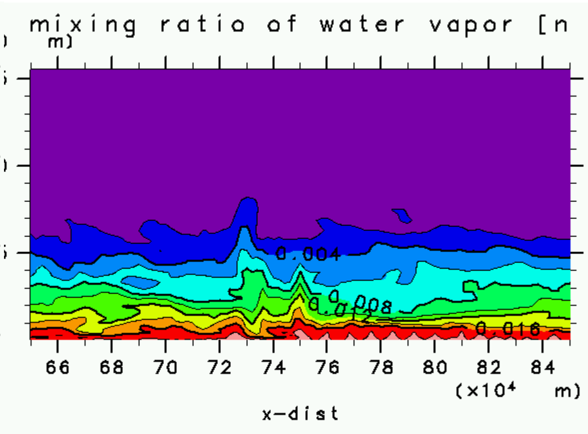


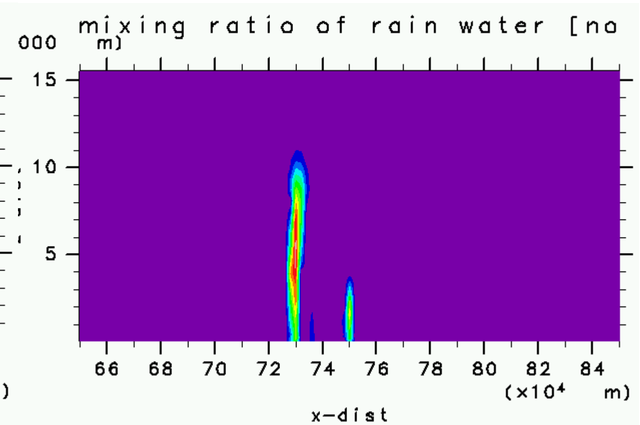


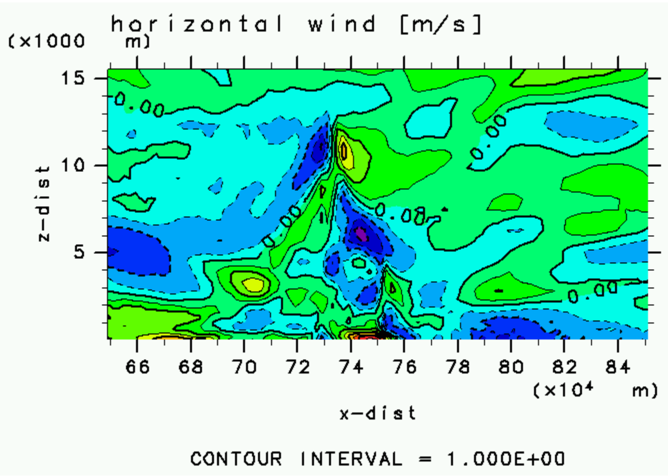


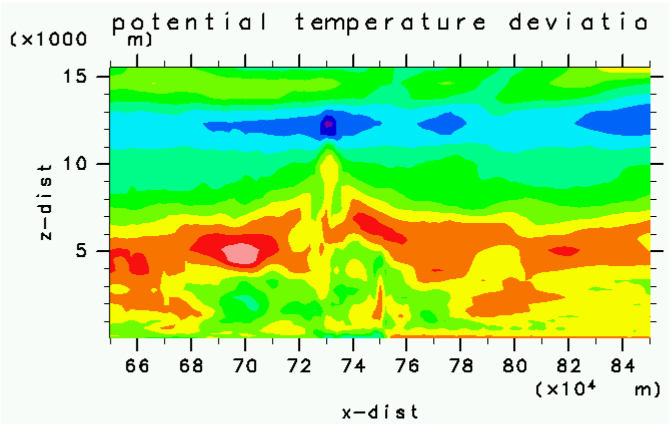
Without threshold for condensation (earth-like composition)



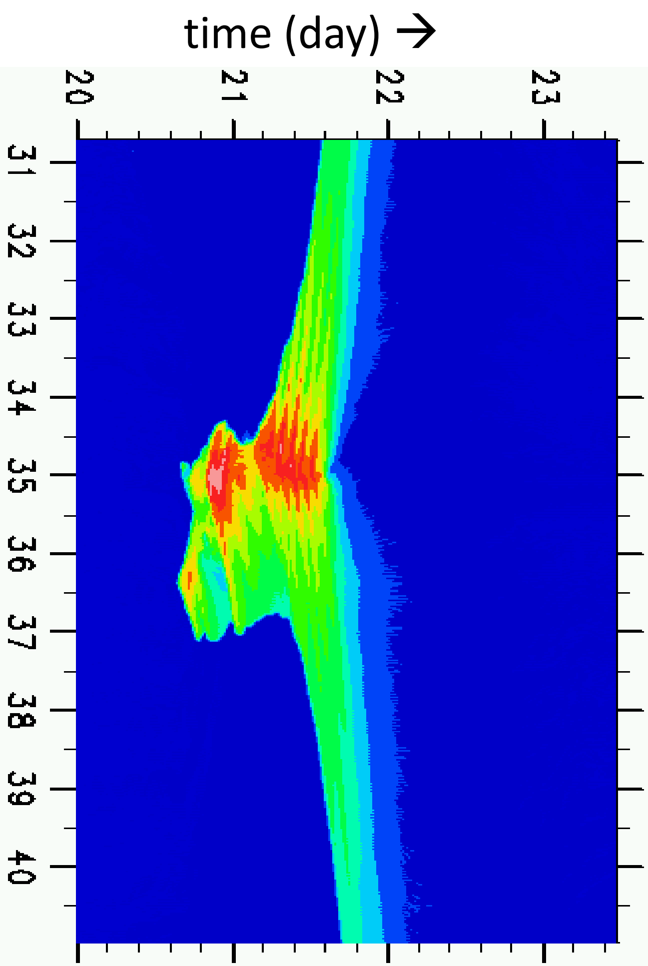




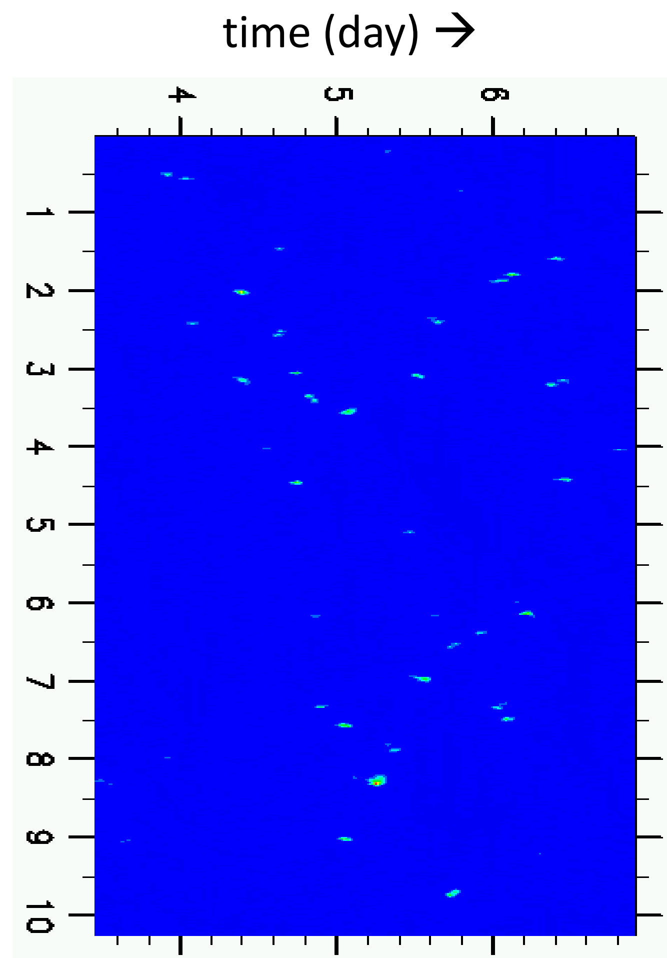




Strength and Life-time may be enhanced with super saturation



<<<<<<<< 1024 km >>>>>>>>>>>>>



Jupiter

NH3 condensation

H2S+NH3 –NH4SH

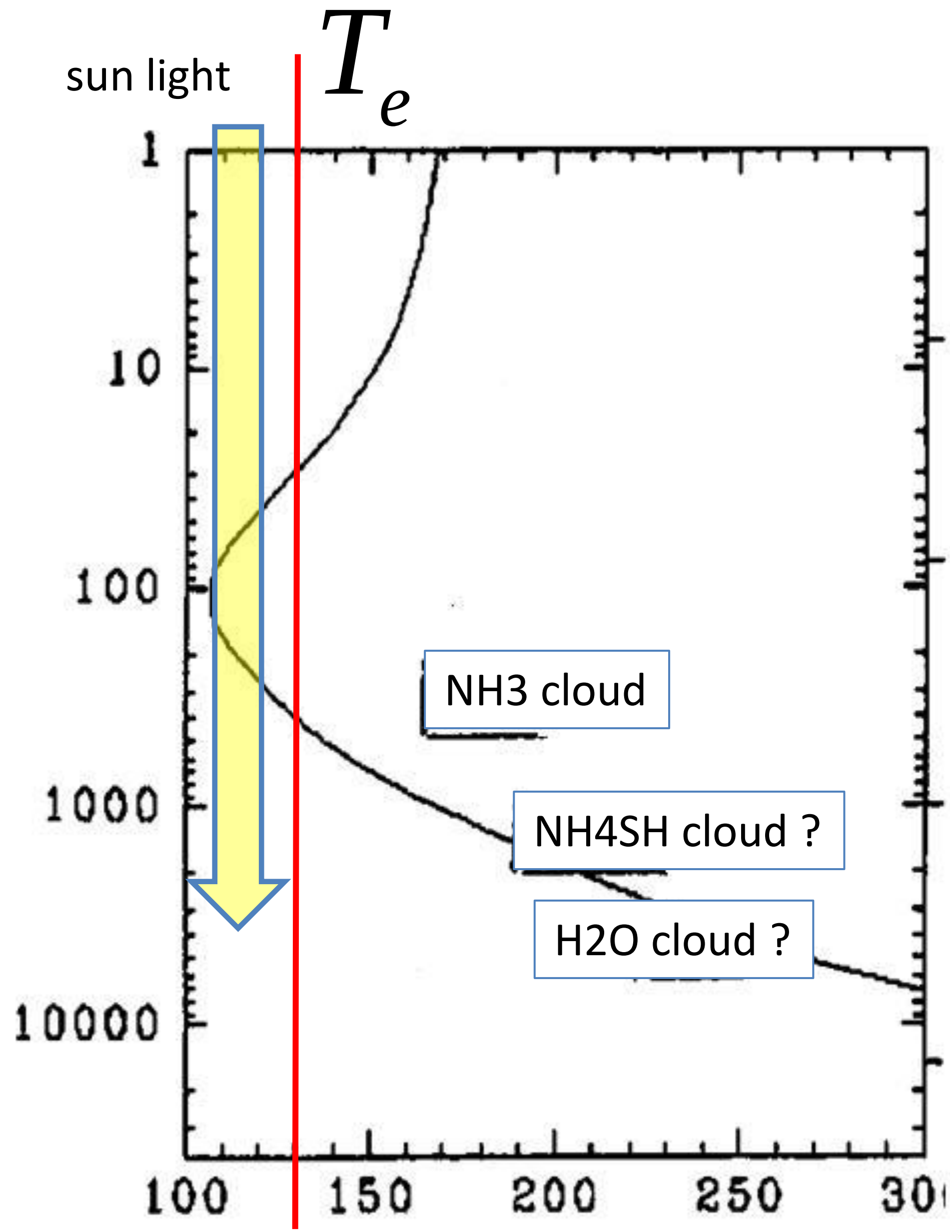
H20 condensation

(H2O NH3 solution?)

Condensable components are heavier than the non-condensable component.

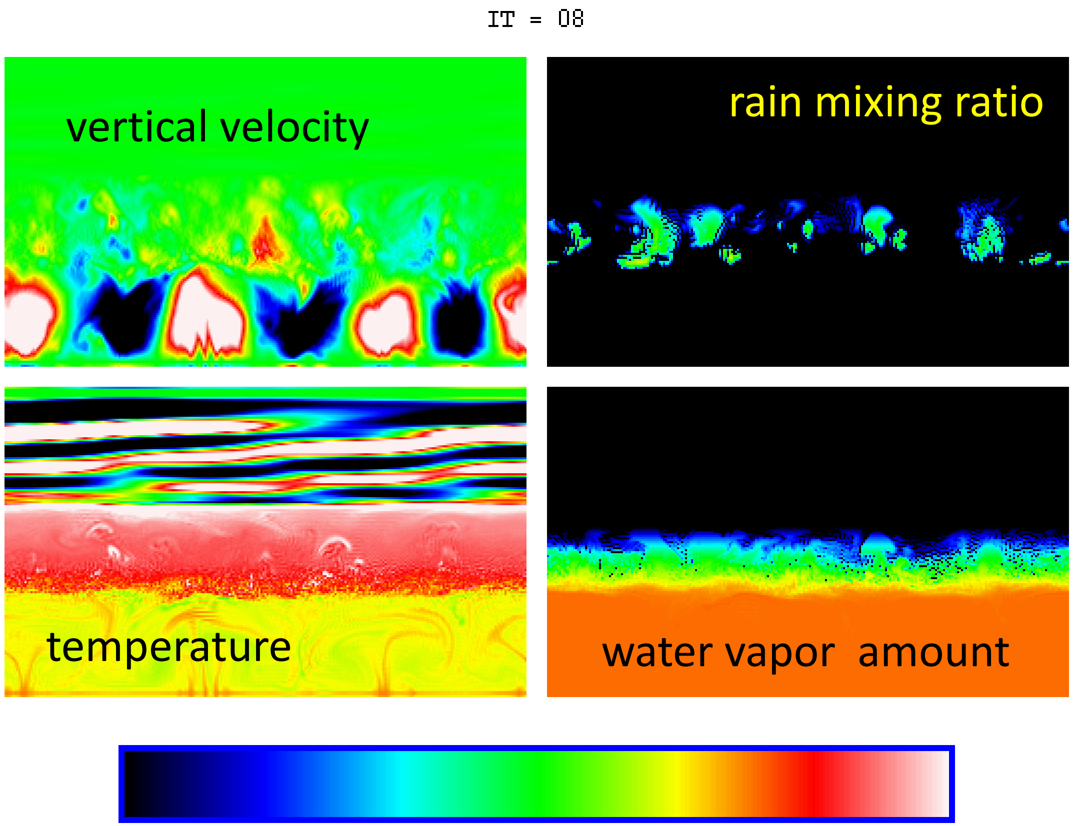
No oceans below.

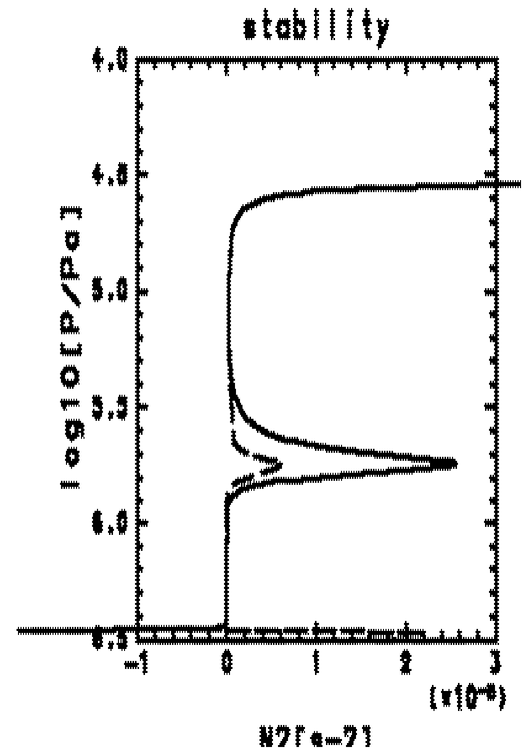
but heat from deep interior, indispensable to keep the atmosphere warm enough to allow active cloud processes.



Nakajima et al(1998)

Jupiter (with H2O only)

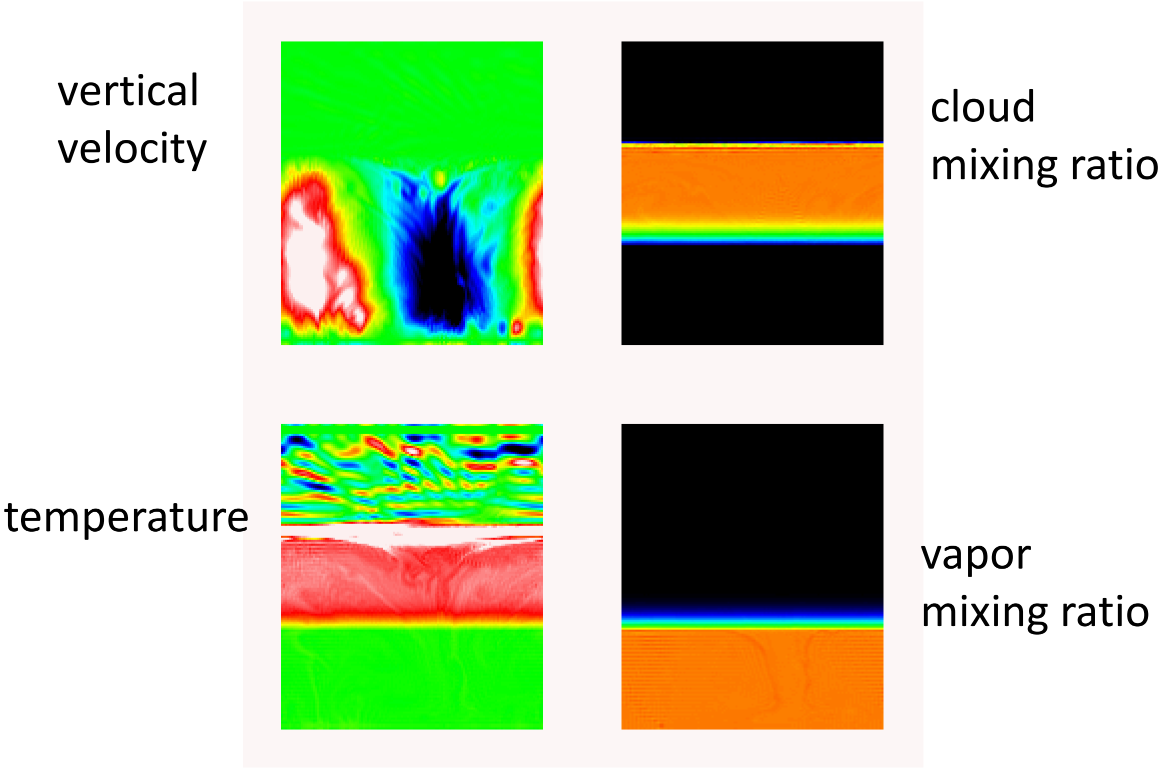




Static stability is dominated by the gradient of mean molecular weight

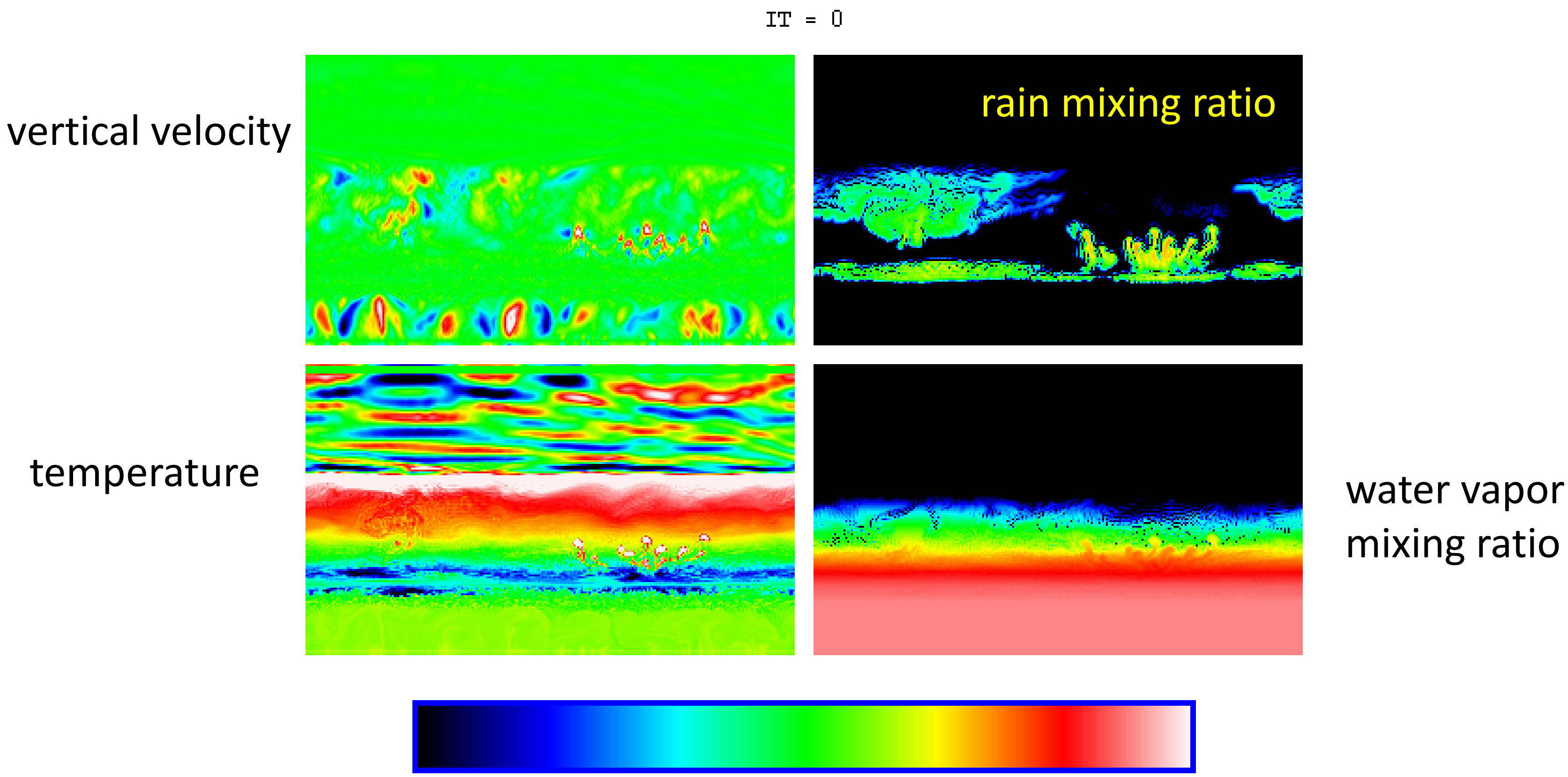
Nakajima et al (1998, 2000)

Case with no cloud physics (no raindrop formation)

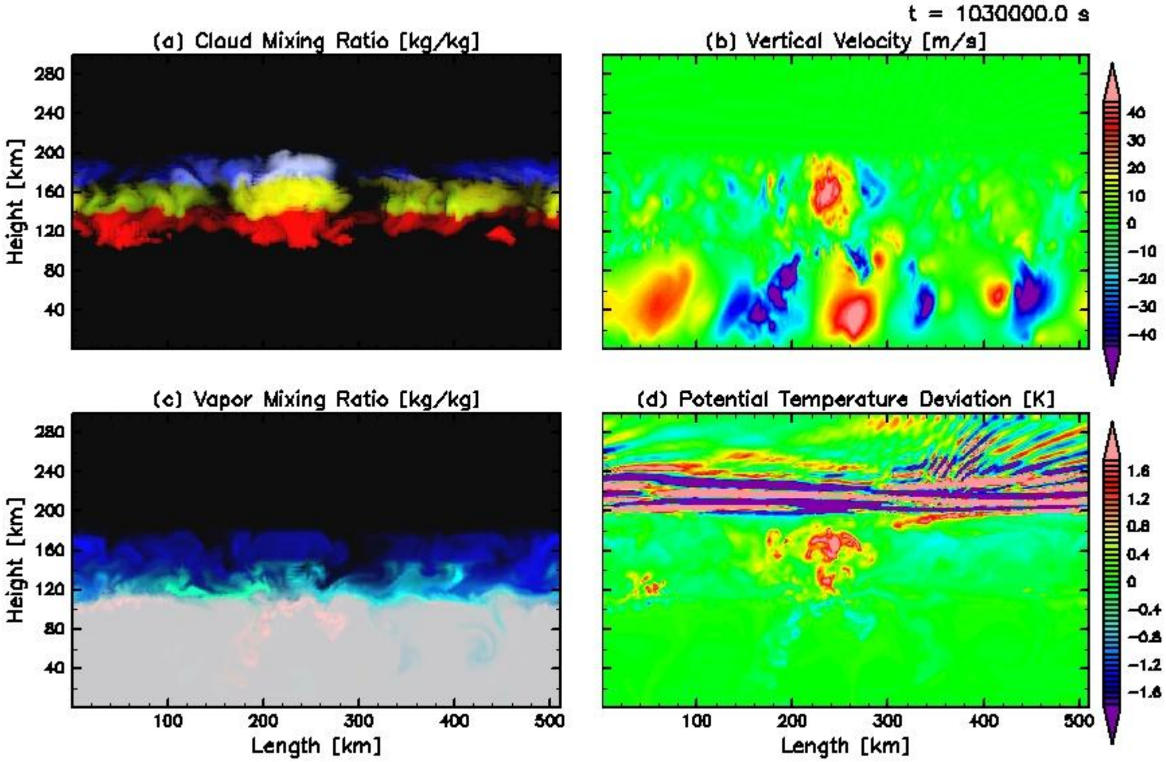


We have another cup of Miso soup.

10 times enhancement of H_2O exceeding the positive buoyancy near the bottom domain

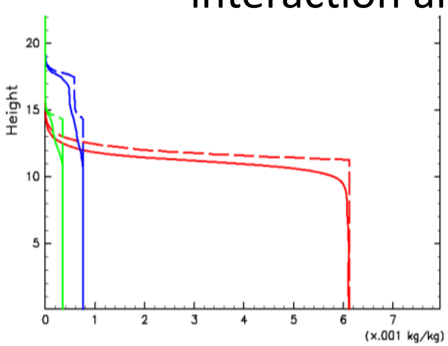


Layered cloud with super adiabatic lapse rate near the condensation level

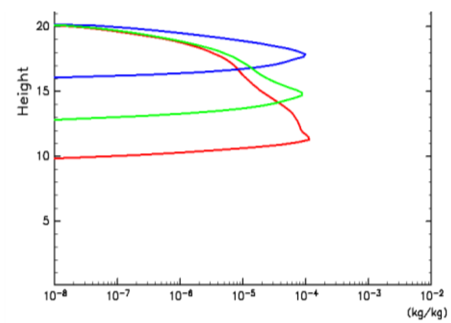


Convection with all of NH_3, NH_4SH, and H_2O clouds Sugiyama et al (2009)

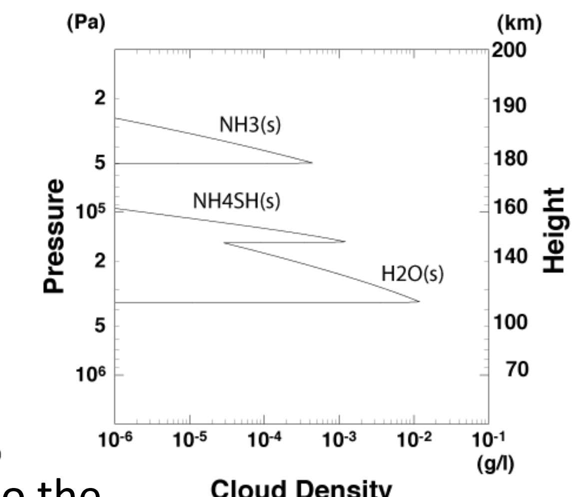
interaction among three cloud layers



NH_3 and H_2S begin to decrease at H_2O condensation level.

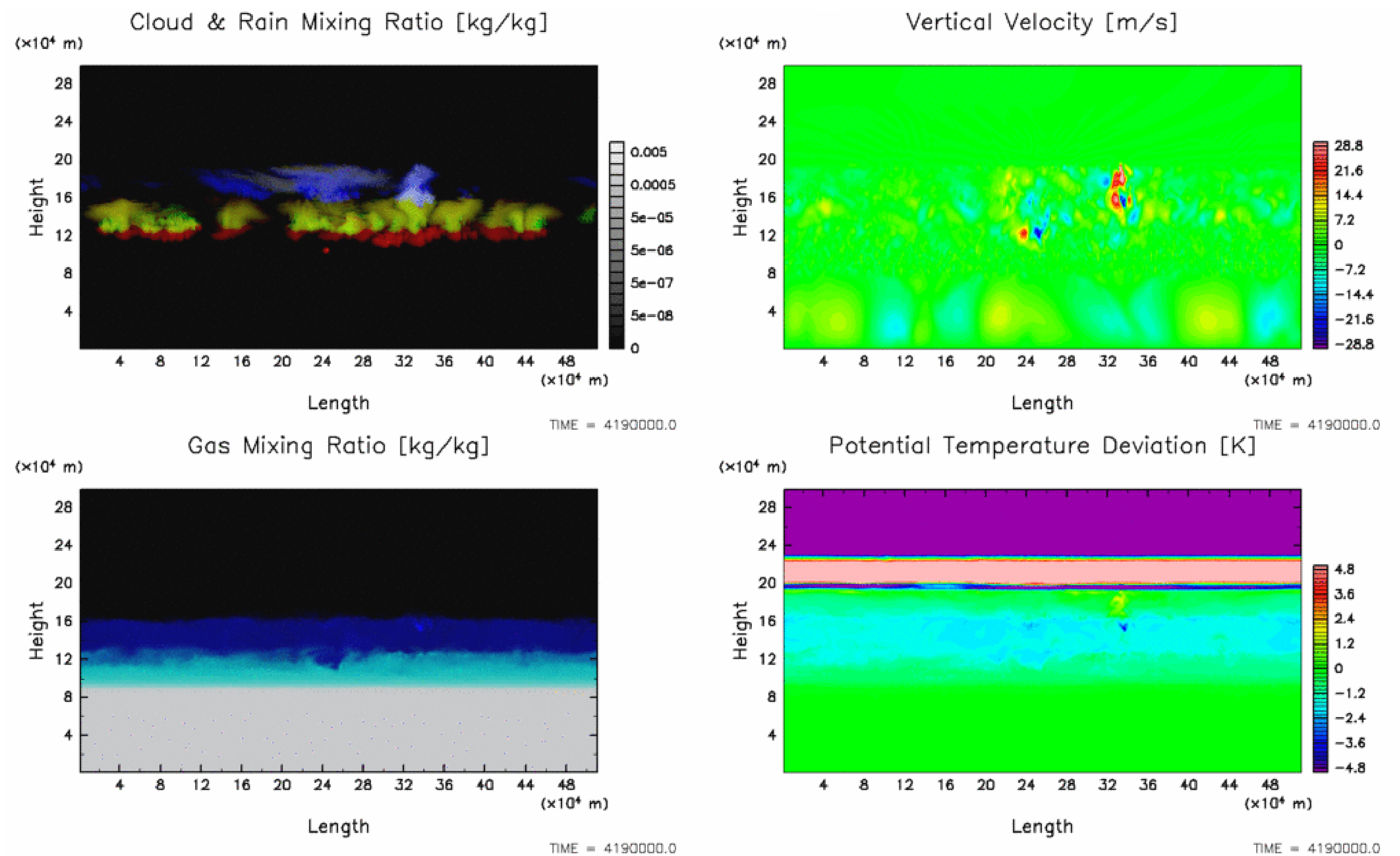


H_2O cloud is transported to the top of NH_3 cloud.

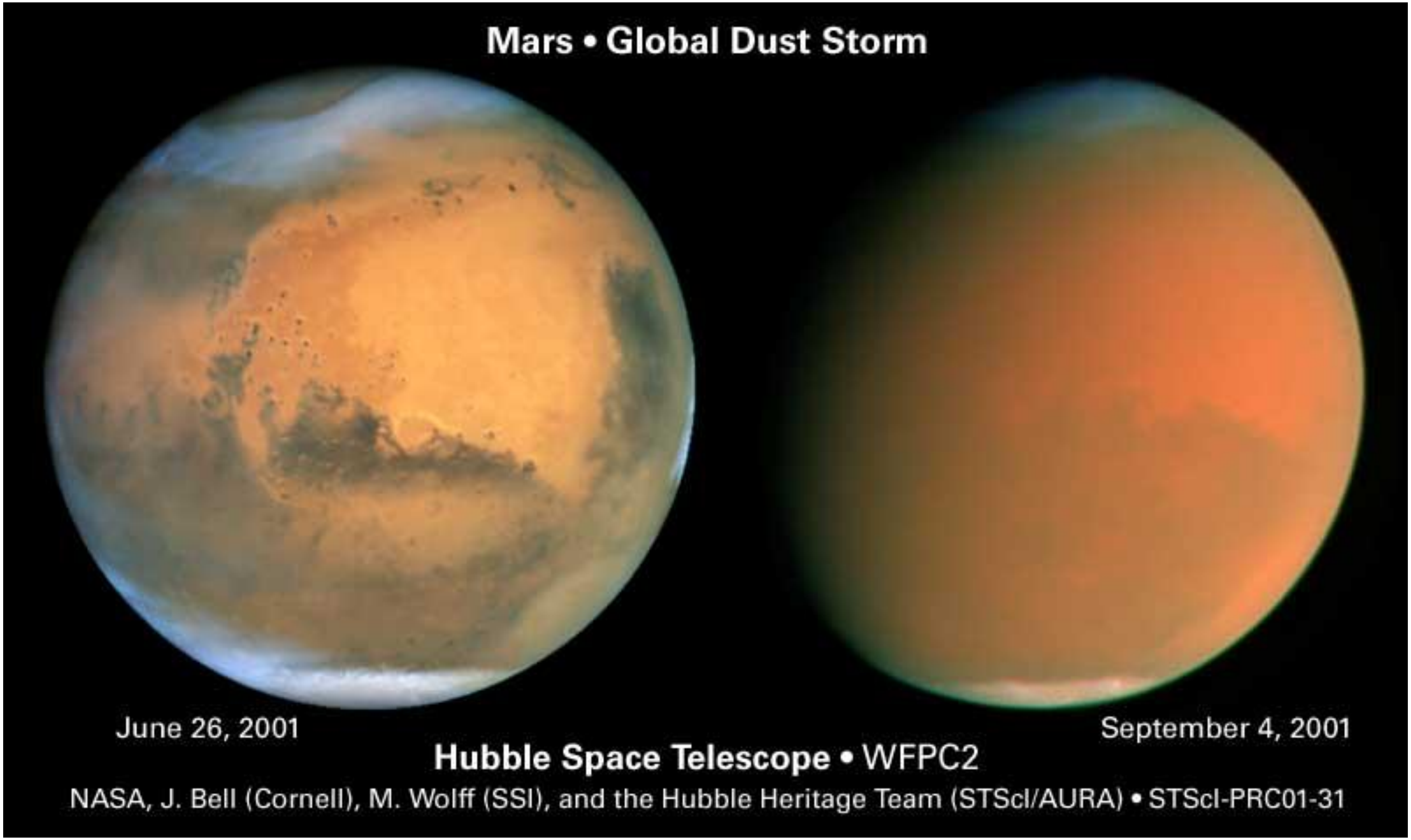


Intermittency of cloud activity (see Sugiyama's poster)

Convection in the "active period" isquite vigorous!

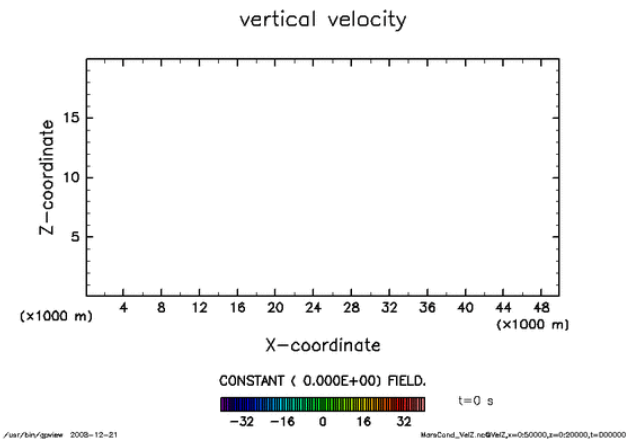


Mars : condensation of major component (CO_2)

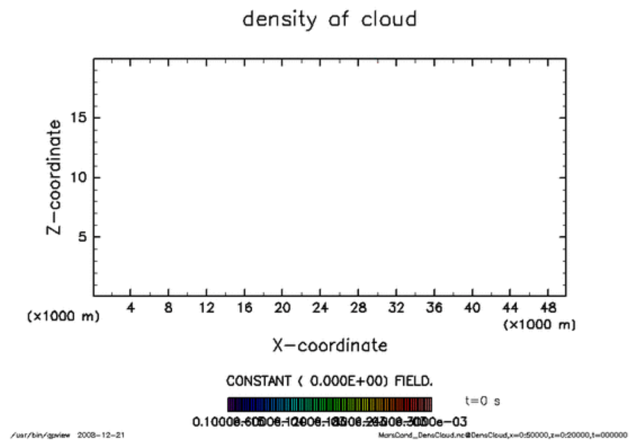


CO2 cloud with condensation at S=135% (See Yamashita's poster)

vertical velocity

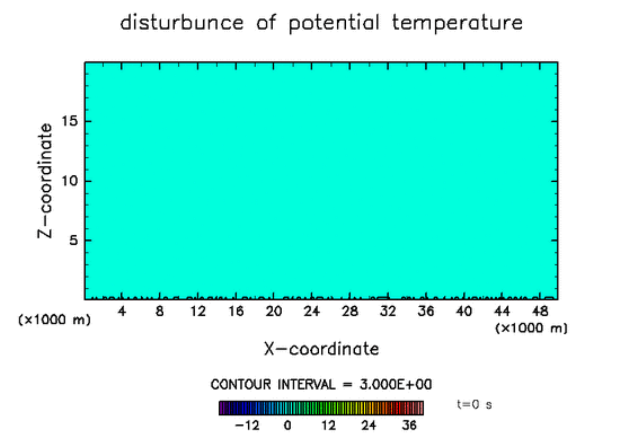


cloud density

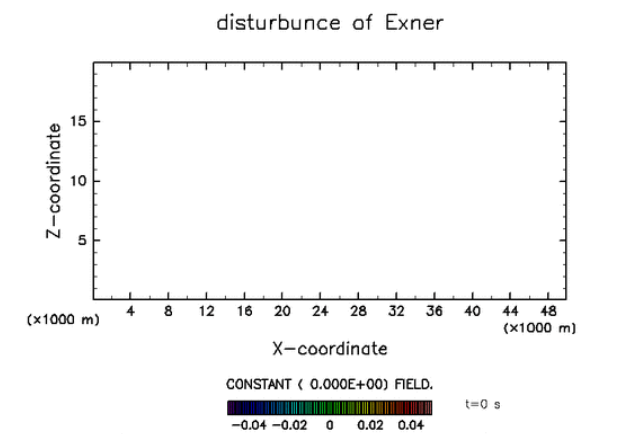


weight of cloud
is not included

transient
towe-like
deep convection



temperature anomaly



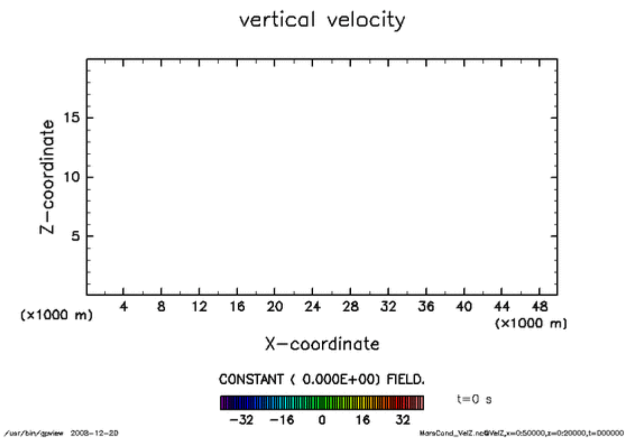
pressure anomaly

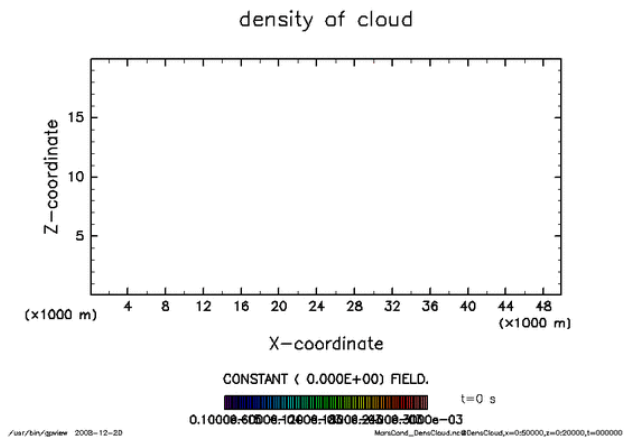
CO2 cloud with condensation at S=100%
(See Yamashita's poster)

vertical velocity

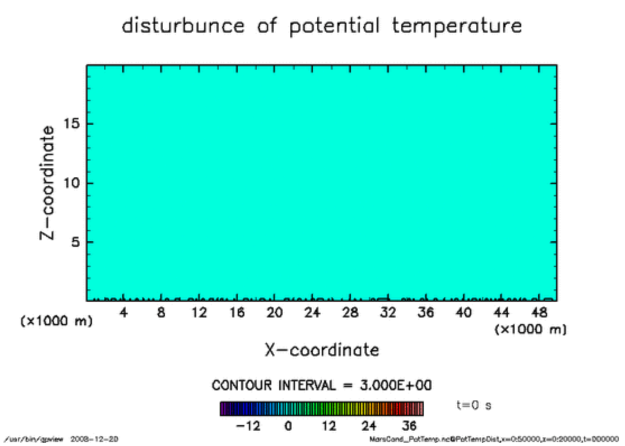
cloud densitv

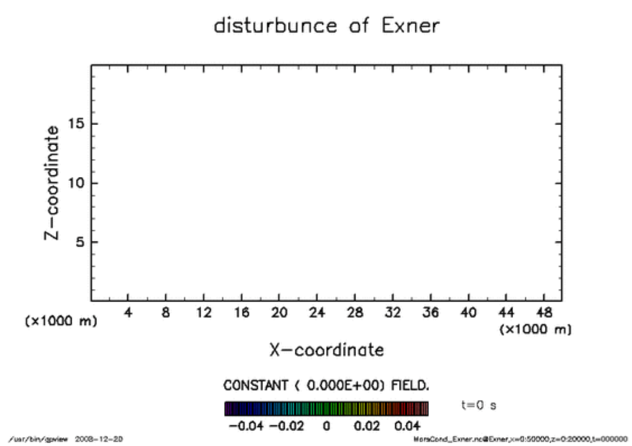
weight of cloud
is not included





no tower-like
convective cloud





temperature anomaly

pressure anomaly

Roles of moist convection in structure and dynamics and so on

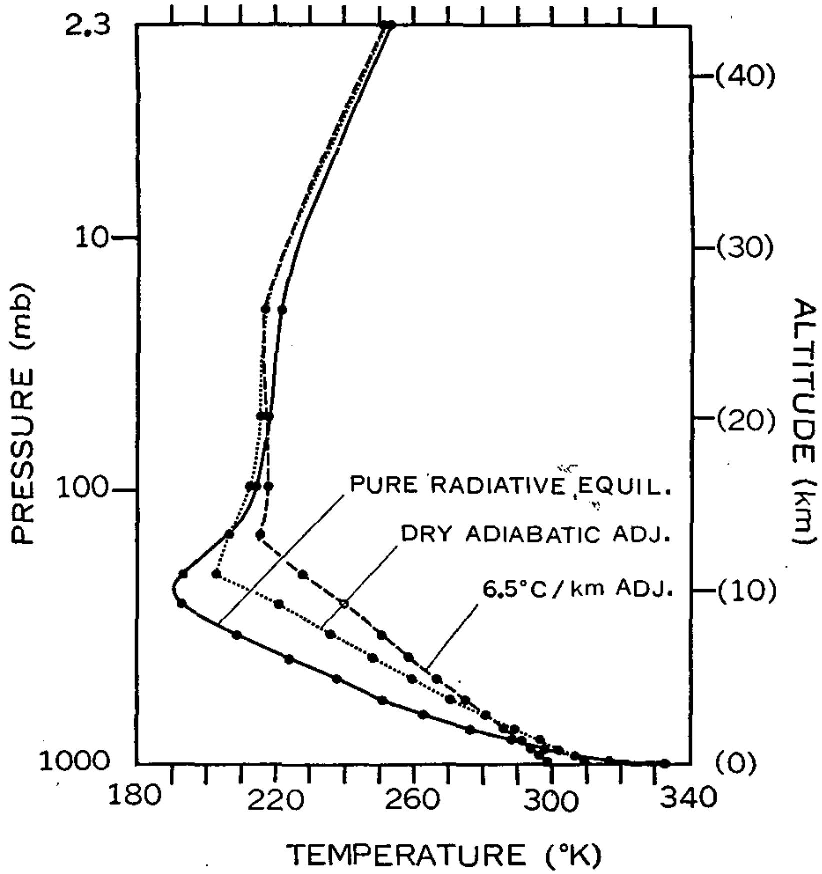
Some examples

- Modification of atmospheric structure

$$\Gamma_m \neq \Gamma_d$$

- Latent heat transport
- Modification of thermodynamic efficiency of the atmospheric heat engine
- Enhancement of vertical coupling
  - land and the atmosphere (e.g. Titan seasonal cycle)
  - "sea" and the atmosphere (e.g. El Nino of the earth)
- Interaction with large-scale flow (Jupiter?)
- Effects on climate through the modification of radiative heating/cooling.

Modification of atmospheric structure

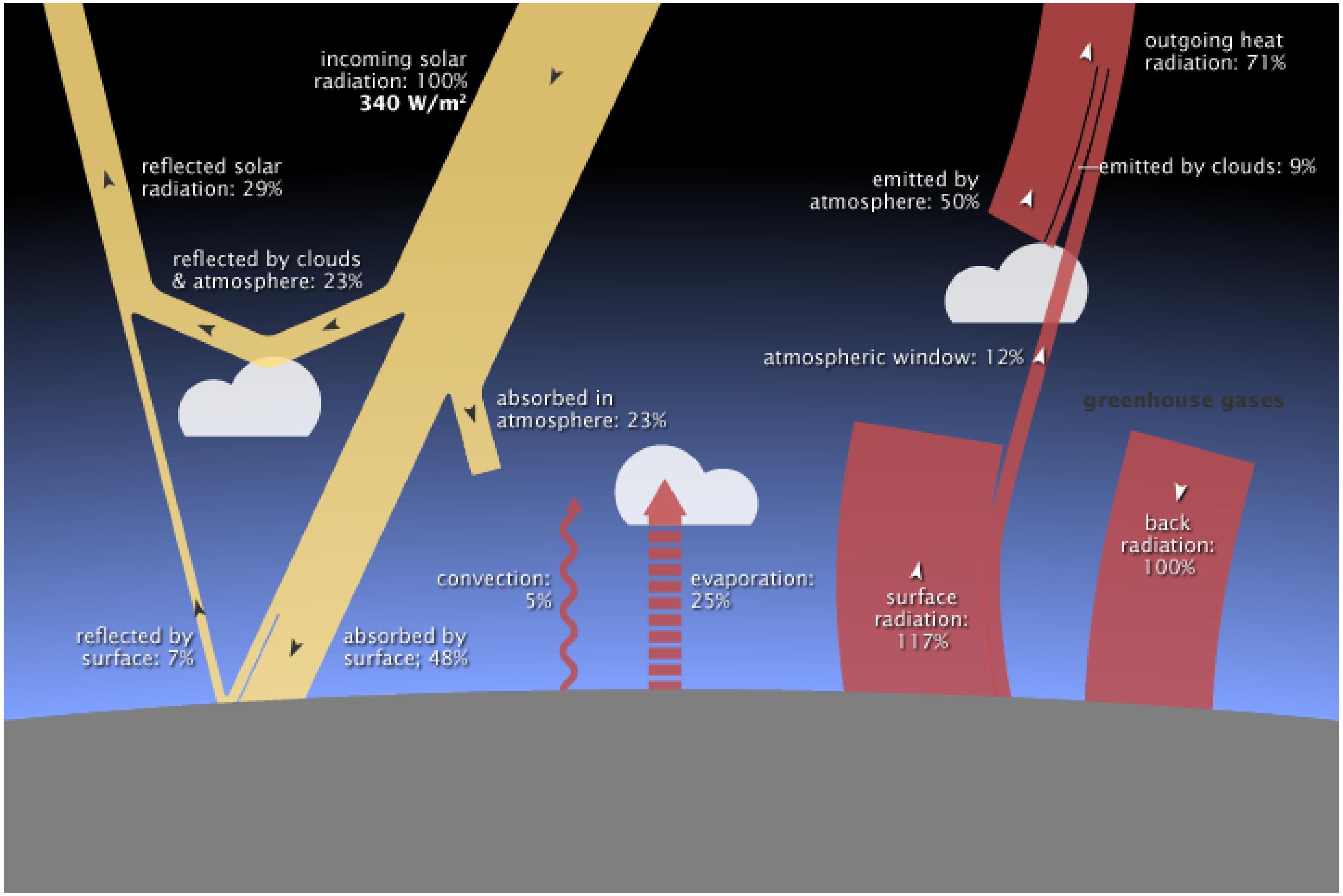


Vertical structure of earth's atmosphere obtained with radiaive-convective equilibrium model.

Inclusion of moist convective adjustment results in
- cooling of lower troposphere
- warming of upper troposphere
- increased depth of troposphere

Manabe and Strickler (1964)

"Latent" heat transport



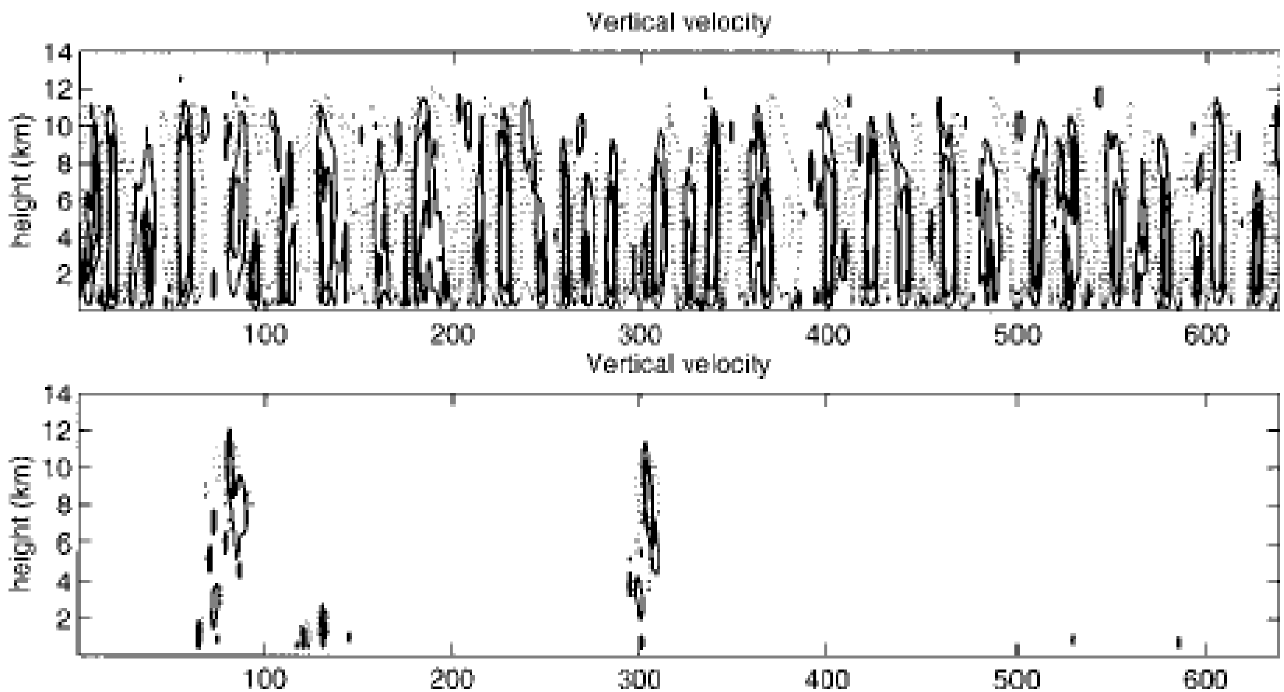
http://earthobservatory.nasa.gov/Features/EnergyBalance

Slow down of convective motion with fixed thermal forcing

Same thermal forcing (heating at the lower boundary and cooling aloft) drives the two systems below, but motion is much vigorous in dry convection!

Dry convection

Moist convection



Pauluis and Held (2002a,2002b)

Cloud convection as a "dehumidifyer" (moisture remover)

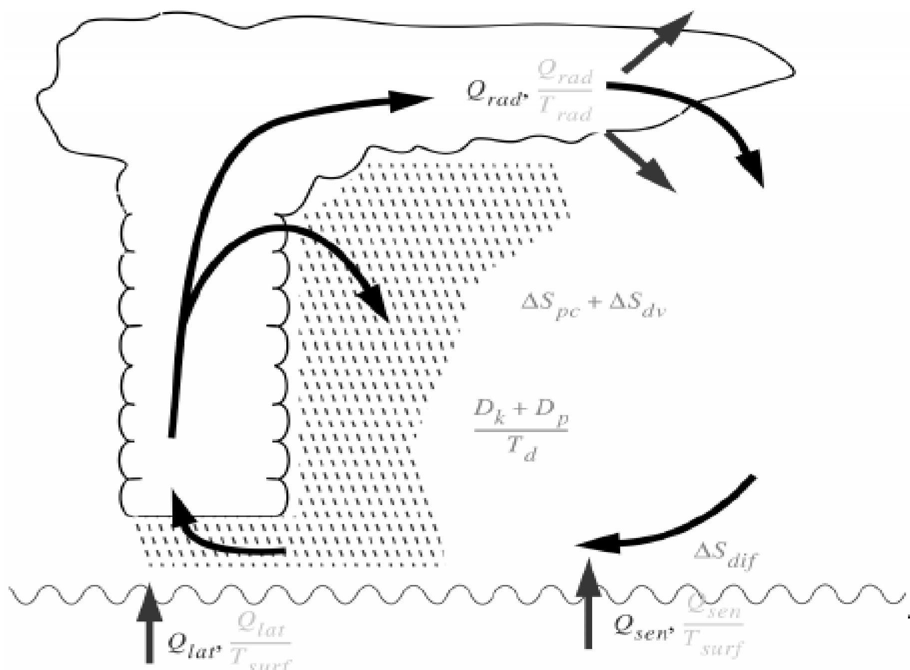


FIG. 1. Schematic representation of the energy and entropy budgets of an atmosphere in radiative–convective equilibrium. The heat sources and sinks are radiative cooling Q_{rad}, surface sensible heat flux Q_{sen}, and surface latent heat flux Q_{lat}. The irreversible entropy sources are frictional dissipation D/T_d, diffusion of heat ΔS_{dif}, diffusion of water vapor ΔS_{dv}, and irreversible phase changes ΔS_{pc}.

Non-equilibrium evaporation lowers the thermodynamic efficiency to 1/3.

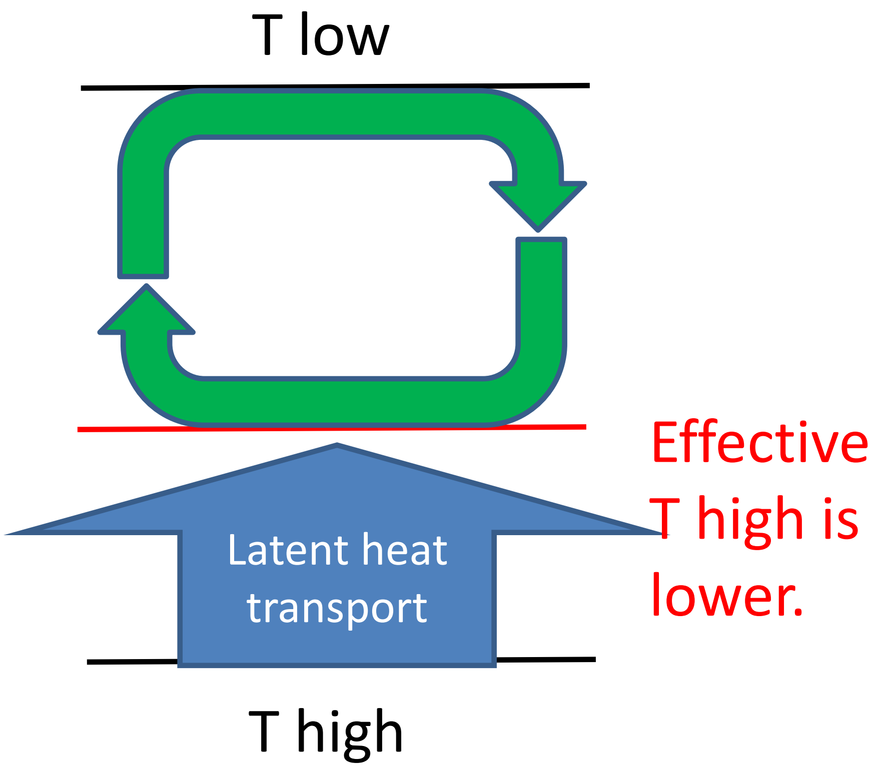
$$\Delta S = M_{evap} R_v \log(R_h)$$

Relative humidity at the sea surface

Pauluis and Held (2002a,2002b), Sugimoto(1985)

The view focusing on non-condensable component

Dry convection



Moist convection

Decrease of △T is quite significant for Earth's atmosphere

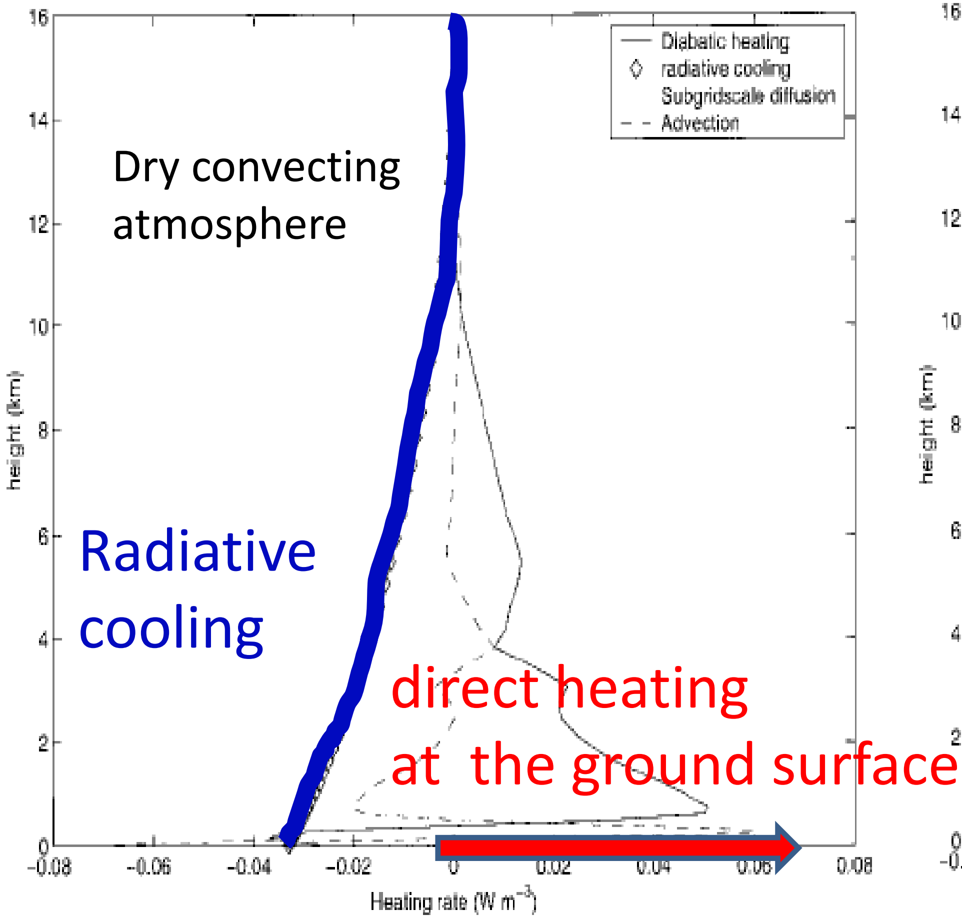


FIG. 5. Horizontally averaged heating rates.

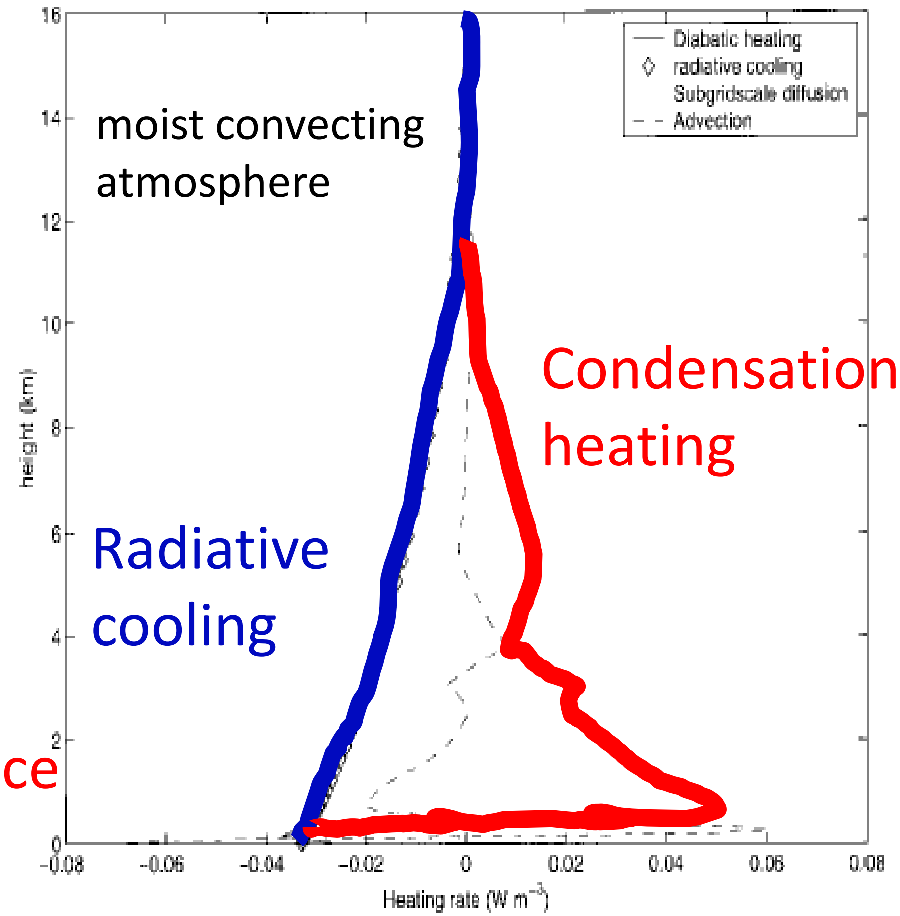


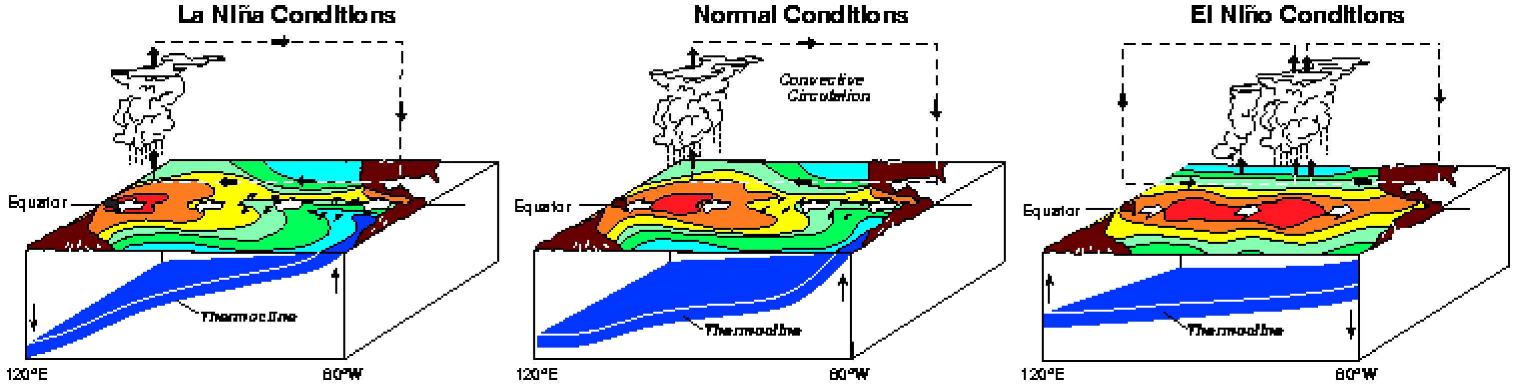
FIG. 5. Horizontally averaged heating rates.

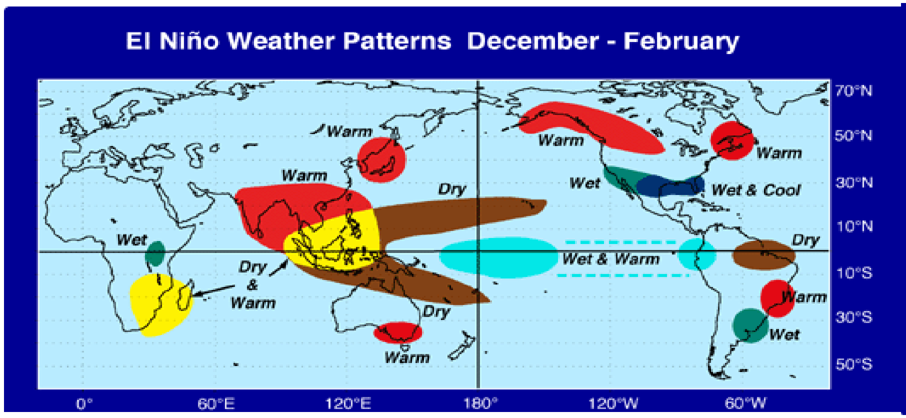
Pauluis and Held (2002a,2002b)

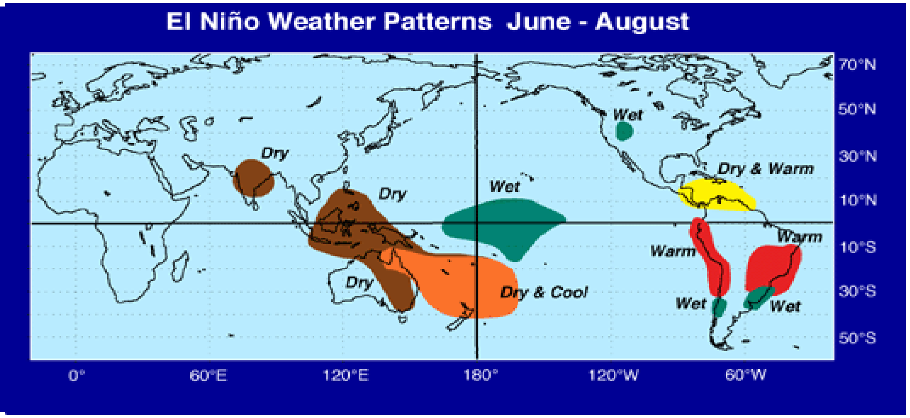
Additional effect may increase the thermodynamic efficiency

- Vertical distribution of radiative forcing may be modified, so that the depth (and the temperature difference) of the convecting layer may increase with moist convection.
- Large-scale structure may increase the temperature of “high-temperature heat source”.
- Even if the efficiency is low, intermittency (in space and time) results in vigorous motion, sometime somewhere.

Result of enhanced vertical coupling by moist convection example 1: $ElNi\tilde{n}o$

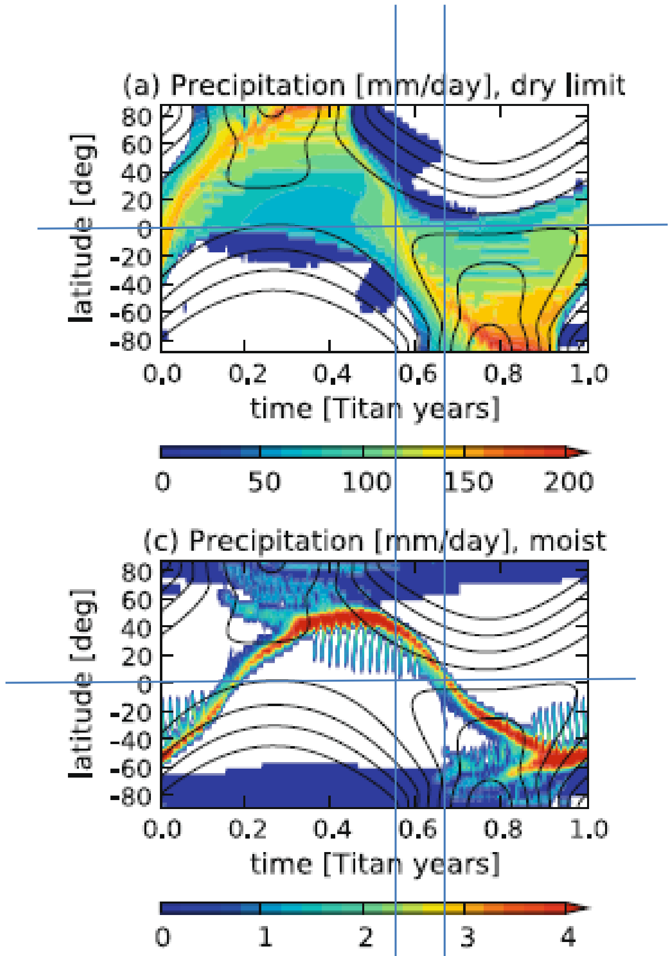




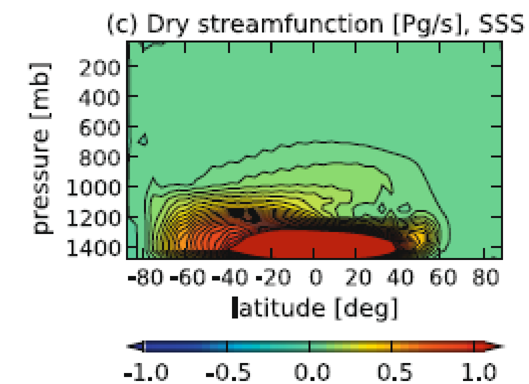


http://www.pmel.noaa.gov/tao/proj_over/diagrams/index.html

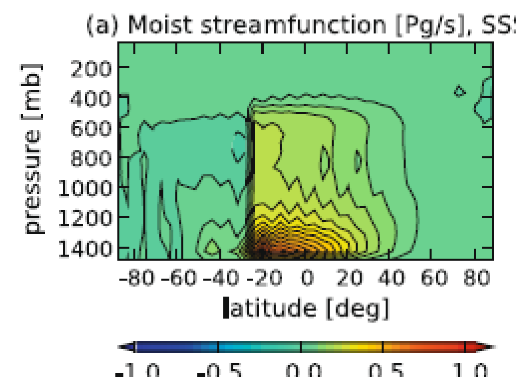
Delay of seasonal cycle (Titan) by enhanced land-atmosphere coupling



dry model



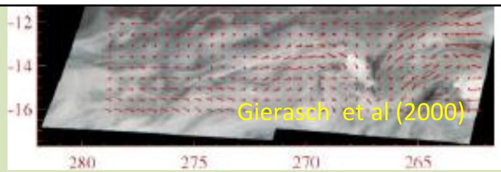
moist model



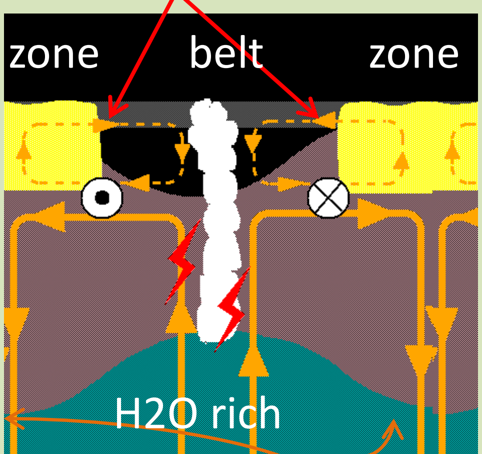
Mitchell et al, Icarus 203 (2009) 250–264

Possible interaction between cloud and zonal-flow

Thuderstorms make eddies and waves affected by Jupiter's rotation.



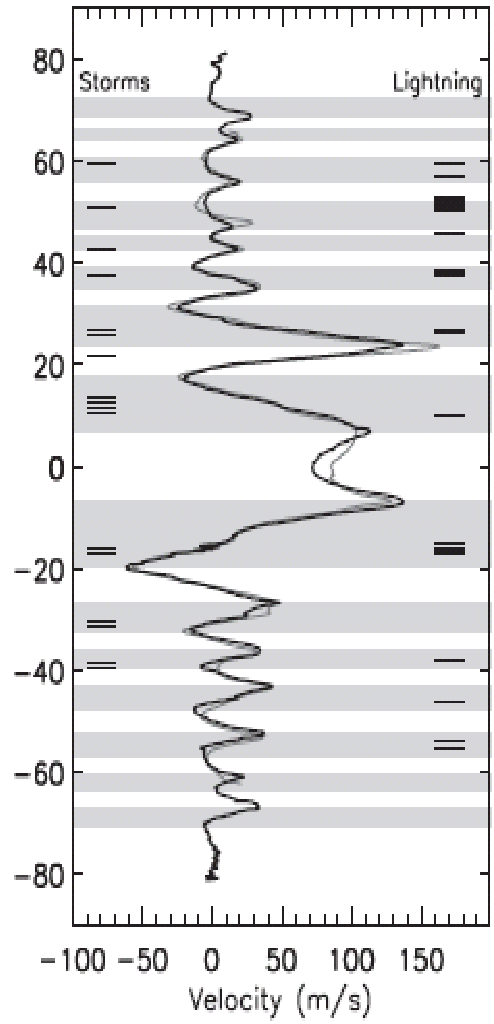
Eddies and waves accelerate the mean east/west flow!
A bit difficult but well- established concept in Planetary Fluid Dynamics.!

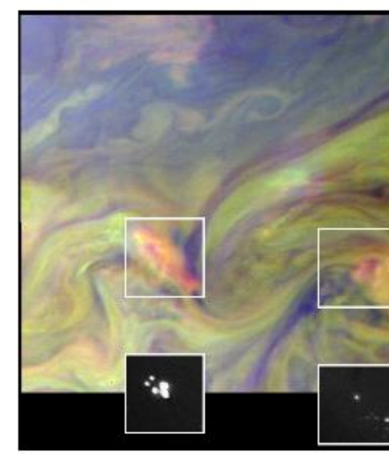


The increase of humidity enhances the activity of thunderstorms at the Belts.

The vertical motion uplift the water vapor rich air from the deep.

The acceleration of mean zonal flow also drives north/south and vertical motion (coming from the effects of the rotation of Jupiter).





Vasavada and Showman(2006)

Concluding Remarks

- Moist convection is working in various planetary atmospheres.
- Properties of convection differ considerably depending on composition, thermal forcing etc.
- Detail of the cloud physics may be important.
- Moist convection affects various aspects of the structure, dynamics, and evolution of the atmosphere.

Thank you for your attention!

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